COMPUTER AIDED MARINE POWER PLANT SELECTION.

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by

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ABSTRACT

The preliminary design sequence for commercial ships with emphasis on power plant selection is examined. It is shown that currently used economic evaluation criteria require that power plant selection be based on an evaluation of the ship-as-a-whole.

A computer program has been developed that aides the proposed power plant selection process. The program models the matching of the ship hull to the propeller with a cavitation criterion applied. It determines the propulsion coefficient and the required propulsion plant size. The program calculates the initial investment cost and the important annual operating costs for steam, diesel and gas turbine power plants.

It is concluded that it is possible to construct a relatively simple model to aid in preliminary power plant selection that can be developed into a computer program.

It is recommended that future studies update and improve the economic cost data, and that data be developed on power plant volumes for use in preliminary design.

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NOMENCLATURE

A_D	=	Developed area of all blades, outside hub
A_E	=	Expanded area of all blades, outside hub
A_O	=	Disc area
A_P	=	Projected area of all blades, outside hub
A_E/A_O	=	Expanded blade area ratio
AAC	=	Average annual cost
C	=	Cargo carried each year
CRF	=	Capital recovery factor
D	=	Propeller diameter
EHP	=	Effective horsepower (bare hull plus appendages)
F_A/F	=	Expanded area of all blades, outside hub (same as A_E/A_O)
h	=	Head of water at screw centerline
i	=	Discount rate
I	=	Initial investment
J	=	Propeller advance coefficient
K_T	=	Propeller thrust coefficient
LHV	=	Lower heating value
n	=	Propeller speed (revolutions per second)
N	=	Project's expected life
PC	=	Propulsion coefficient
PI	=	Profitability index
PV	=	Present value
P/D	=	Pitch diameter ratio
r	=	Internal rate of return
R	=	Net annual cash flow

RPM	=	Propeller speed (revolutions per minute)
SFC	=	Specific fuel consumption
t	=	thrust deduction fraction
T	=	Thrust
V	=	Ship speed
V_A	=	Speed of advance
w	=	Taylor wake fraction
η_{HULL}	=	Hull efficiency
η_{PO}	=	Propeller open water efficiency
η_r	=	Relative rotative efficiency
η_{SHAFT}	=	Shaft transmission efficiency
ρ	=	Density of water (lb-sec^2/ft^4)
$\sigma_{0.7R}$	=	Cavitation number at 0.7 tip radius
τ_C	=	Cavitation index

1. INTRODUCTION

The preliminary selection of the power plant for commercial ships is a decision process which must translate propulsion technology into economically measurable quantities. Early in the design sequence, it is necessary to restrict the need for detailed studies to those plants which will be economically competitive. Therefore, it is desirable to have a relatively simple model that will enable the naval architect, the power engineer, and the ship owner to make such a selection.

It is important that the power engineer realize that this evaluation and selection process can be made only when the ship-as-a-whole is evaluated. Several studies which attempt to show that one type of plant is superior to another but which consider only the acquisition, installation and annual operating costs have been performed and published. Such studies frequently treat the propulsion plant as a separate system and do not go on to evaluate the impacts that the different plants have on the ship configurations and thus the changes in payload carrying capability and power requirements. They therefore do not give an accurate estimation of the economic tradeoffs involved in power plant selection.

It is the purpose of this paper to (a) present an approach to the preliminary design sequence that considers the ship-as-a-whole with emphasis on the role of the power engineer and the interfaces he must consider, and (b) develop a computer program that will assist in the power plant selection process at the preliminary design stage.

First, the preliminary design is discussed. Currently used economic evaluation criteria are reviewed to illustrate the need to consider the

entire ship system in power plant selection.

Next, it is shown how the requirements generated by the ship owner and the naval architect can be utilized in the selection of an optimum efficiency propeller which satisfies a cavitation criterion. It is then shown how the propulsion plant size can be determined.

The initial investment costs and significant annual costs for steam, diesel and gas turbine plants of single screw ships in the 10,000 SHP to 50,000 SHP range are developed.

A computer program was written and its features are presented. It utilizes the propeller selection procedure and cost functions previously discussed. The program is a simple tool which can aide in focusing attention on those plants worth the time and expenditure for detailed design and evaluation.

Finally, the conclusions and recommendations are presented.

2. PRELIMINARY DESIGN AND ECONOMIC CRITERIA

An approach to preliminary design is presented with emphasis on power plant selection. The current methods utilized in making economic comparisons are presented and some conclusions on how they impact the preliminary design are made.

2.1 PRELIMINARY DESIGN

The entire ship design process begins with a statement of owner requirements. This can be for a single ship or fleet of ships. In order to consider the full spectrum of possible alternatives and thus focus on the system which will provide the best economic solution, the requirements should be general. The statement will specify the type of ship payload, the ship routes, and an estimate of the amount of capital available for the initial investment.

It should then be the function of the naval architect and operations analyst to examine the alternatives available. Generally, this involves examining ships of different displacements, payload carrying capabilities and sustained operating speeds that can be obtained within the investment restrictions imposed. The revenue generating capacities and costs involved in operating as well as the investment costs are evaluated using one of the techniques shown in the next section of this chapter to determine the range of hull displacements, cargo carrying capacities, and ship speeds which will be evaluated in more detail. Because of the complex nature of ship design and thus the lack of current models to perform the above to a reasonable degree of accuracy, it is realized that such studies are currently subject to many limitations. It is to be pointed out, however, that too frequently the

ship speed and/or payload capabilities are specified early in design with little or no systematic evaluation of the economic tradeoffs. The computer model herein developed can be utilized as one portion of a model to perform such studies.

The next step in the preliminary design should be to take a limited number of payload capabilities, ship speeds and required endurances (i.e., ship routes) and perform more detailed analysis. The naval architect here determines basic hull forms (reference 1) and displacements based on past design experiences to establish the power requirements (bare hull plus appendages), the wake fraction, the thrust deduction factor, and the relative rotative efficiency. In determining the hull form, an allowance for weight, compartment length, compartment volume, and vertical and longitudinal centers of gravity for the propulsion plant must be assumed by the architect. The hull form is defined by basic dimensions of length, beam and draft plus hull coefficients of form. With the hull form defined, the power requirements are determined from such models as the Taylor Standard Series, the Series 60 or other proprietary data the naval architect has available (reference 1). This process also allows determination of the maximum propeller diameter allowed and an approximate shaft centerline depth.

Utilizing the analytical techniques summarized in reference 2, a propeller can be matched to the performance requirements and hull characteristics. This process is developed in Chapter 3 and is also included as part of the computer program. Utilizing the cavitation criterion in reference 3, it is not unreasonable to make consideration of the limitations imposed and the resultant reduced propeller efficiency at this stage of the design process. This criterion is also included in the computer program developed.

The important parameter determined in the last step is the propeller open water efficiency. This allows determination of the propulsion coefficient and thus the power requirements of the propulsion plant. If the propeller RPM determined is not compatible with the capabilities of direct drive slow speed diesels, a separate propeller calculation must be performed utilizing the propeller RPM constraint (see Chapter 3), and thus a propulsion coefficient and power requirement for that plant are determined.

At this point in the preliminary design, the power engineer can determine initial costs associated with different types of power plants. The types to be considered in this paper are non-reheat and reheat steam, slow and medium speed diesels, and two gas turbine plants. The costs considered are treated in detail in Chapter 4 and are part of the computer program.

The power engineer must then examine the weights, volumes, lengths, and centers of gravity for the different plants. He must then interact with the naval architect and the owner to make adjustments to the original hull forms. Several alternatives are possible and the limit on how many will be evaluated will be a function of the time and resources available (determined by the owner). The alternatives include maintaining the hull form and size and altering payload capabilities or maintaining payload capabilities and altering hull form to conform to the plant. It is realized that the latter implies an alteration in power requirements and thus a change in plant size. The implication of this is that the process is iterative and should involve good communication between the owner, naval architect and power engineer.

The process of determining both hull forms and plant characteristics at this time is thus generally not one of optimization, but rather one of sufficiency. In the past, this has been because of the limitations of time and

resources on performing all of the iterations desired by the engineer to find an optimum plus a lack of theory which will allow development of an optimum hull form. It will be seen that the computer program developed reduces the time required for determination of an optimum propeller and allows for rapid determination of significant costs. It can therefore be utilized as one element to expand the alternatives that can be considered and thus help remove some of the first limitations of the past.

At the completion of the preliminary design there will be several alternatives which can be evaluated by the economic criteria established. Analysis of these results will then indicate which system or systems should then be examined in more detail and proceed to the contract design stage. It is observed that the propulsion plant has been integrated into the whole ship and the resultant overall system evaluated against the other alternatives.

2.2 ECONOMIC CRITERIA

There are several methods for making economic comparison of competing alternatives that are in current use by both financial managers and marine engineers. There is considerable literature available which explains them in detail. There are also many opinions regarding which criteria are best and when to use them. No attempt will be made to present these aspects. A good summary of them is presented in reference 4. The criteria are presented below in order to determine the impact they should have on power plant selection methods.

2.2.1 Payback Period (reference 5)

The payback period is the number of years it takes a firm to recover its original investment from net returns before depreciation but after taxes.

It requires estimates of future cash flow (revenues and expenses) when evaluating investment alternatives.

2.2.2 Present Value (references 4 and 5)

The present value (PV) method takes into consideration the concept of the time value of money, i.e., a dollar today is worth more than a dollar tomorrow. To compare investments, the present value of the expected net cash flows, discounted at the discount rate (cost of capital), are determined and the costs of the initial investments are then subtracted. The projects can then be ranked by the net returns. The equation for determining present value is

$$PV = \left[\frac{R_1}{(1+i)^1} + \frac{R_2}{(1+i)^2} + \ldots . \frac{R_N}{(1+i)^N}\right] - I = \sum_{t=1}^{N} \frac{R_t}{(1+i)^t} - I$$

where R_t is the net cash flow in year t; N is the project's expected life; i is the discount rate and I is the initial investment. For the special case where the net cash flow each year is uniform, the equation reduces to

$$PV = R \left[\frac{(1+i)^N - 1}{i(1+i)^N}\right] - I$$

This is also called the discounted cash flow (DCF) method.

2.2.3 Profitability Index (references 4 and 5)

The profitability index (PI) (benefit/cost ratio or present value index) is calcultated by dividing the present value of future returns discounted at the discount rate by the initial investment

$$PI = \frac{\sum_{t=1}^{N} \frac{R_t}{(1+i)^t}}{I}$$

2.2.4 Internal Rate of Return (references 4 and 5)

The internal rate of return (IRR) (or interest rate after tax) is defined as the interest rate that equates the present value of expected future

returns to the initial investment costs

$$I = \sum_{t=1}^{N} \frac{R_t}{(1+r)^t}$$

The value of r that satisfies this equation is the internal rate of return. The solution for r is iterative.

2.2.5 Capital Recovery Factor (reference 4)

The capital recovery factor (CRF) is that term which is obtained by dividing the uniform annual returns by the initial investment. Rather than be used as a criterion itself, it is generally used to find the implied interest or yield rate that the calculated returns provide. It can be shown that

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1}$$

Tables are usually used to determine i knowing the value of CRF and N. This is the specialized case of the IRR method for uniform annual returns.

2.2.6 Average Annual Cost (reference 4)

The average annual cost (AAC) method converts all costs to an equivalent uniform amount. This must include the annual cost of capital recovery of the investment. When this method is used to compare alternatives, the revenue generating capability of the alternatives must be the same.

2.2.7 Required Freight Rate (reference 4)

The required freight rate (RFR) is the rate that the shipowner must charge his customers if the owner is to earn some reasonable return on his investment. Alternatively, it can be that freight rate which allows the ship owner to break even on his investment. In the simple case where annual costs are uniform and cargo transported annually is uniform

$$RFR = \frac{AAC}{C}$$

where AAC is average annual cost and C is the cargo carried each year.

All of the above require a knowledge of net cash flow each year, or the assumption that annual revenues are the same, or a knowledge of the cargo carrying capabilities of the alternatives in order to choose the economically optimum. Since alternative power plants have specific impact on the ultimate ship configuration and thus the cargo capacity and/or power requirements, it is demonstrated that the ship-as-a-whole concept is the proper way to compare alternatives and should be the basis for power plant selection.

3. DETERMINATION OF PROPELLER CHARACTERISTICS AND PROPULSION COEFFICIENT

A simple procedure is developed for the determination of propeller characteristics utilizing the diameter and RPM constraints on Wageningen B-screw series, B4-40 to B4-100 and B5-45 to B5-105, and imposing a 5% back cavitation criteria. The method for determining the propulsion coefficient is presented.

3.1 MATCHING THE PROPELLER AND THE HULL

The development of the correlation between the propeller characteristics and the external ship characteristics, commonly called the diameter constraint, is presented in reference 2. This relation is

$$K_T/J^2 = \frac{EHP \cdot 550}{V^3 \cdot D^2 \cdot \rho \cdot (1-w)^2 \cdot (1-t)} \qquad (1)$$

where K_T = propeller thrust coefficient

J = propeller advance coefficient

EHP = effective horsepower (bare hull + appendages)

V = ship speed (feet/second)

D = propeller diameter (ft)

ρ = density of water (lb-sec^2/ft^4)

w = wake fraction

t = thrust deduction fraction

Utilizing the definition of the advance coefficient

$$J = \frac{V_A}{n \cdot D} \qquad (2)$$

where $V_A = V(1-w)$

= speed of advance

and (1), a relation called the RPM constraint is developed

$$K_T/J^4 = \frac{EHP \cdot 550 \cdot n^2}{V^5 \cdot \rho \cdot (1-w)^4 \cdot (1-t)} \tag{3}$$

where n = propeller speed (revolutions per second)

For most commercial ships in the range considered for this paper, one of the above constraints will determine the propeller characteristics. The diameter constraint (K_T/J^2) applies for plants which utilize a prime mover with high rotational speeds and a reduction gear to match the propeller. The RPM constraint may govern for the direct drive diesel.

Utilizing a propeller chart such as shown in Figure 1 and the procedure described in Appendix A of reference 2, the propeller characteristics are determined for the given diameter or RPM constraint. Simply stated, K_T/J^2 (or K_T/J^4) is calculated for the known ship characteristics and plotted on the chosen propeller chart. The number of blades and the expanded blade area ratio (A_E/A_0 or F_A/F) are the parameters defining the chart used. An optimum efficiency point is determined and then the corresponding pitch-diameter ratio (P/D ratio) and advance coefficient are established. See Figure 2.

A cavitation check must then be performed (described in section 3 of this chapter). If the cavitation criterion is not met, the propeller calculation must be repeated for a larger expanded blade area ratio and rechecked for cavitation. It frequently requires several iterations before a satisfactory solution is obtained.

3.2 IMPROVED METHOD FOR ANALYTICAL PURPOSES

There is a method of presenting the propeller data which simplifies the above procedure and which can also be readily adopted for use on the computer. A series of K_T/J^2 and K_T/J^4 curves can be plotted on a given propeller chart and the maximum efficiencies and corresponding P/D ratios and advance

Figure 1.

Propeller Characteristic Chart

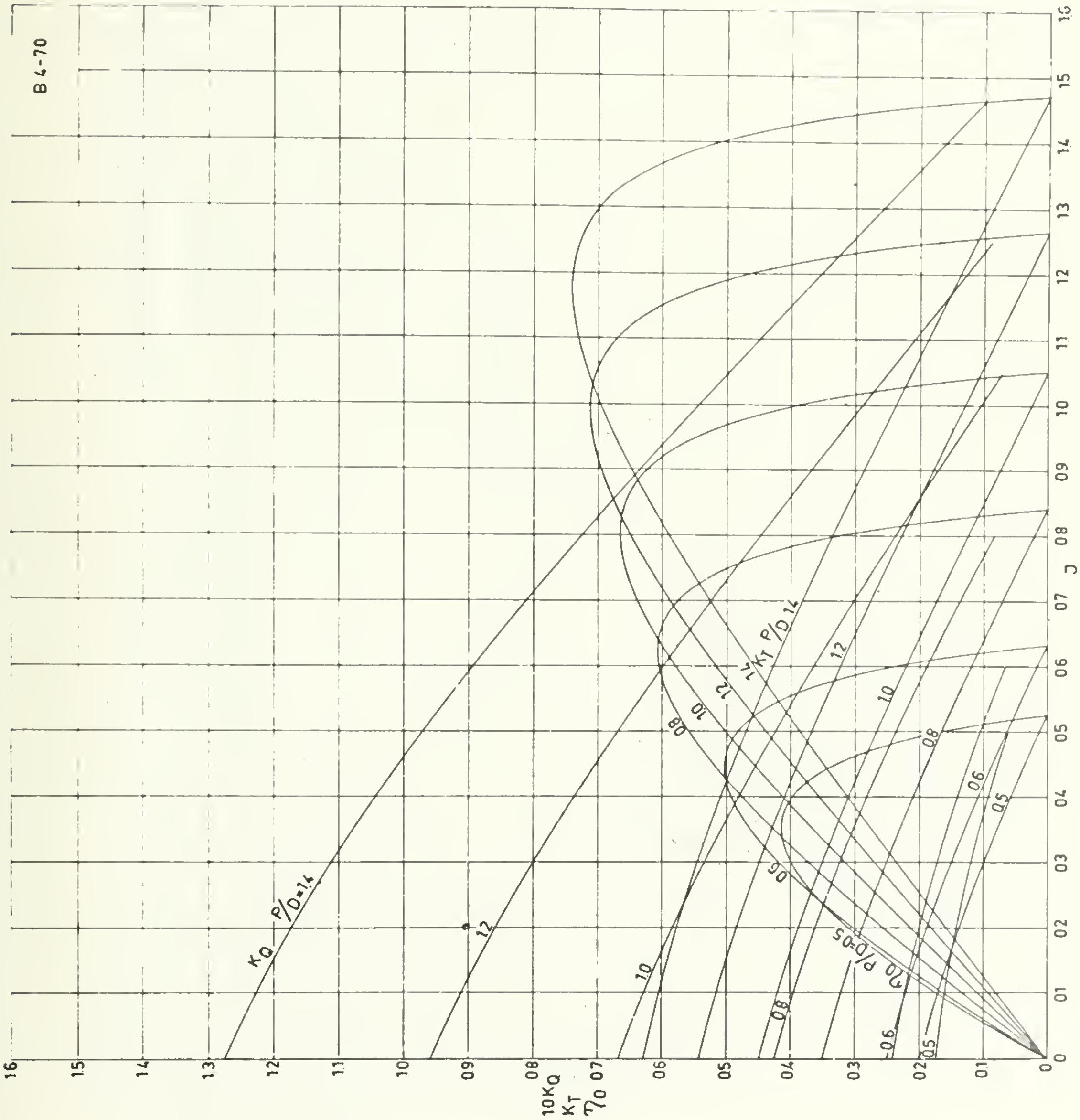
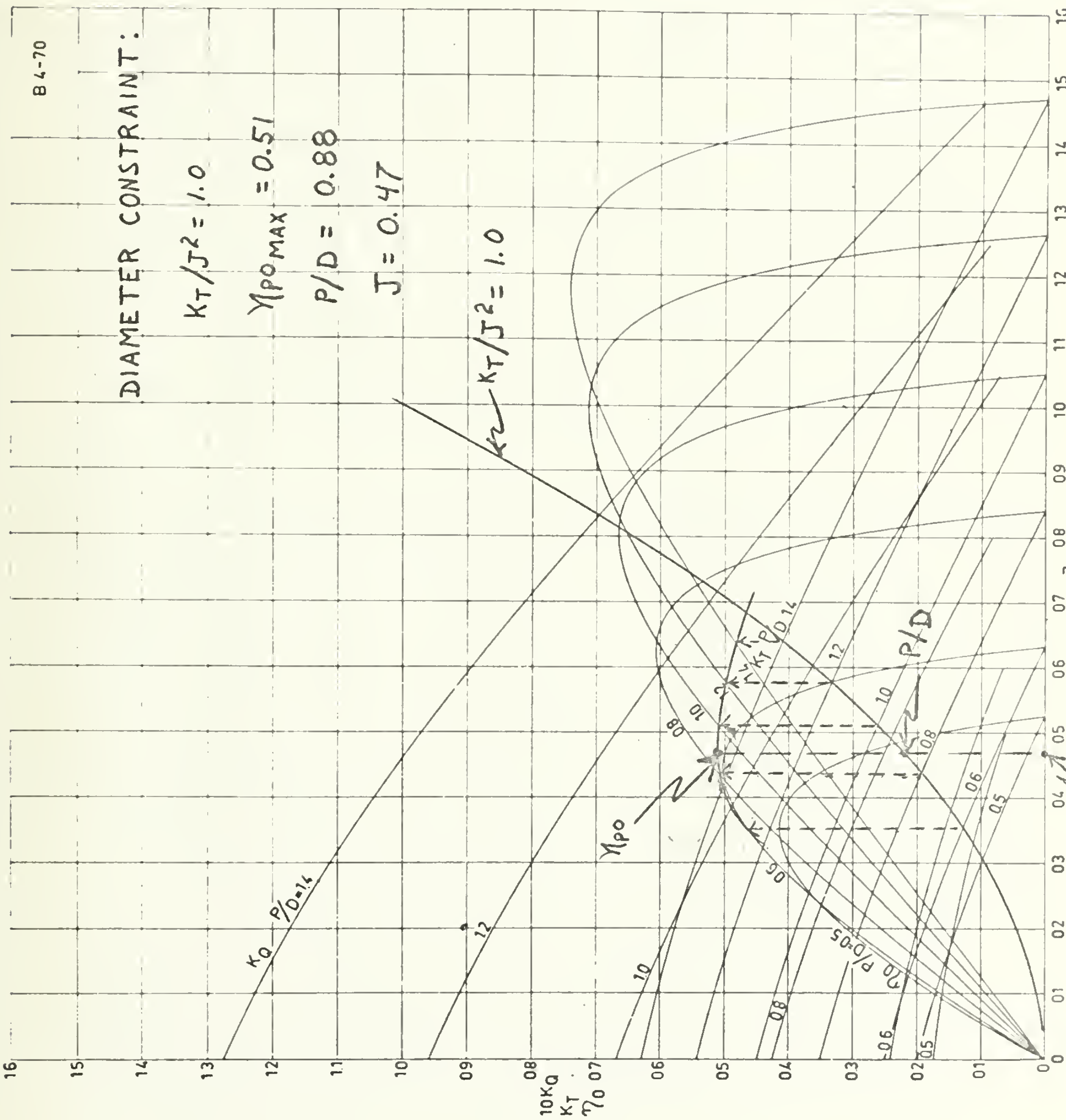


Figure 2.

Determination of Optimum Propeller

Characteristics from Diameter Constraint



coefficients determined. The data generated can then be presented graphically as shown in Figure 3.

Reference 6 contains similar graphs for recently updated data for the Wageningen B4-40, B4-55, B4-70, B4-85, B4-100, B5-45, B5-60, B5-75 and B5-105 propellers. Graphs for the B4-40, B4-100, B5-45 and B5-105 which were developed from the above are included in Appendix A. It is approximated for the four- and five-blade propellers with intermediate blade area ratios that the propeller characteristics can be determined by linear interpolation between the B4-40 - B4-100 and the B5-45 - B5-105.

Use of the graphs in Appendix A can significantly simplify the work involved in propeller calculations for analytical work.

3.3 CAVITATION

Cavitation is a phenomenon which occurs on highly loaded propellers in which, beyond certain critical revolutions, there is a progressive breakdown in the flow with a consequent loss of thrust. It also manifests itself by noise, vibration and erosion of the propeller blades, struts, and rudders.

To minimize cavitation, the blade area is increased in order to reduce the thrust loading. Examination of the open water efficiency curves shows that η_{PO} can vary as much as 9% between the B5-45 and B5-105 propellers. This is significant and should be considered in preliminary design.

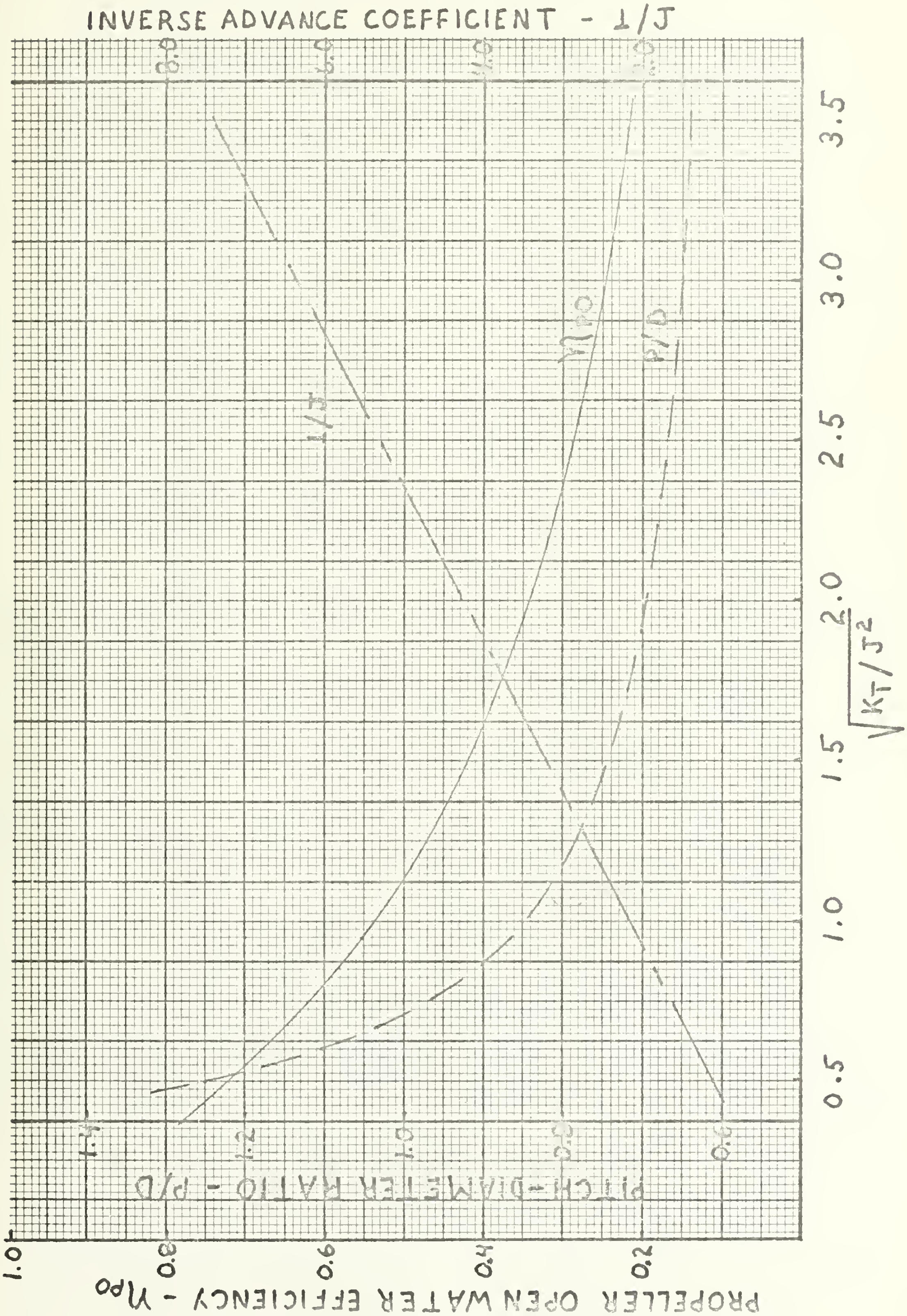
A procedure for determining the cavitation characteristics of a propeller was developed by Burrill in 1943 and is presented in reference 3. A coefficient, τ_C, expressing the mean thrust loading on the blades is defined as

$$\tau_C = \frac{T/A_P}{\frac{1}{2}\rho(V_R)^2} \qquad (4)$$

and is plotted against the local cavitation number at 0.7 tip radius, $\sigma_{0.7R}$.

Figure 3. Optimum Propeller Characteristics

Versus Diameter Constraint



T = thrust (lb.)

$$= \frac{EHP \cdot 550}{(1-t) \cdot V \cdot 1.6915} \qquad (5)$$

V = ship speed (knots)

A_P = projected blade area (ft^2)

$$= (1.067 - 0.229\ P/D)\ A_D \qquad (6)$$

$$A_D = F_A/F\ (\pi \frac{D^2}{4}) \quad (ft^2) \qquad (i.e., F_A/F \simeq A_D/A_O) \qquad (7)$$

D = propeller diameter (ft)

Let $q_T = \frac{1}{2} \rho\ (V_R{}^2)$

$$= [(\frac{V_A}{7.12})^2 + (\frac{nD}{329})^2] \quad (psi) \qquad (8)$$

where $V_A = V\ (1-w)$ (V in knots)

Then

$$\sigma_{0.7R} = \frac{p_0 - p_v}{q_T} \qquad (9)$$

where $p_0 - p_v = 14.45 + 0.45\ h$ (10)

and h = head of water at the screw centerline (ft)

τ_C is calculated using (5) - (8) and

$$\tau_C = \frac{T/(A_P \cdot 144)}{q_T} \qquad (11)$$

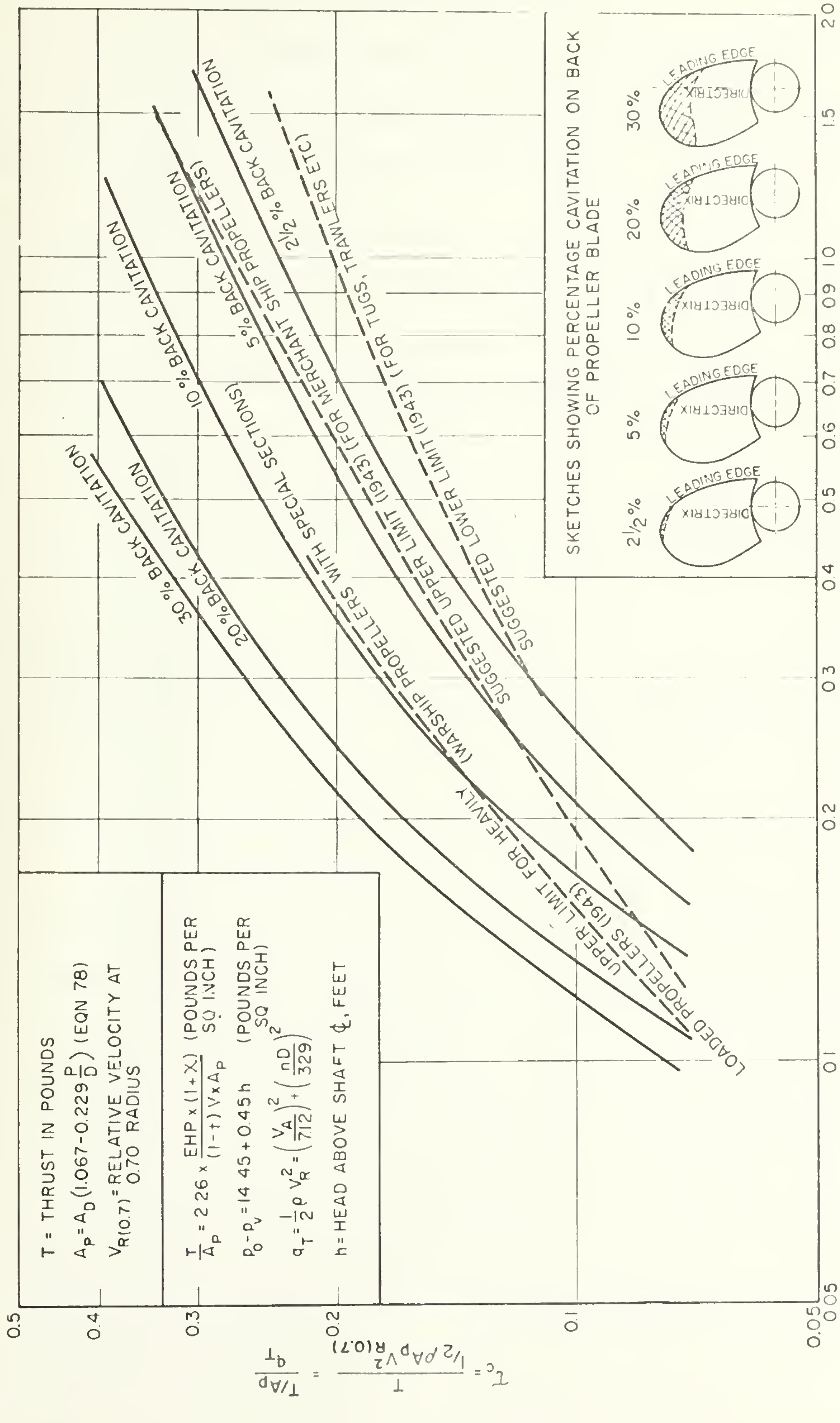
and $\sigma_{0.7R}$ is calculated from (9).

The Burrill type cavitation chart is shown in Figure 4.

Several studies have been performed on what criteria are acceptable as cavitation criteria. On the basis of studies as recent as 1968, reference 3 states "...the line indicating 5 percent back cavitation (is) a suitable criterion at which to aim in practical design calculations."

For this paper the 5 percent criterion as shown on the Burrill chart is accepted. Therefore, τ_C from (11) must be less than the τ_C which

Figure 4. Cavitation Chart



corresponds to $\sigma_{0.7R}$ from (9) on the chart.

3.4 A PROCEDURE FOR DETERMINING PROPELLER CHARACTERISTICS

For purposes of analysis in estimating the propeller open water efficiency and satisfying the 5% back cavitation criterion the following sequence can be followed.

a. Calculate the diameter or RPM constraint as applicable from (1) or (2).

b. Utilizing the graphs in Appendix A, determine the P/D and 1/J for for the B4-40 or B5-45 as desired.

c. Determine the propeller speed (n = revolutions per second) if diameter constraint or propeller diameter (ft) if RPM constraint from (2).

d. Calculate $\sigma_{0.7R}$ from (9).

e. Determine the τ_C limit for 5% back cavitation from Figure 4.

f. Calculate T from (5).

g. Calculate A_P required from

$$A_P = T/(q_T \cdot \tau_C)$$

h. Calculate A_D from (6).

i. Calculate the minimum required expanded blade area ratio, F_A/F, from

$$F_A/F = A_D/(\pi \frac{D^2}{4} 144)$$

If this is less than or equal to the F_A/F chosen in step b, the η_{PO} can be determined from the graphs in Appendix A. If the F_A/F obtained is greater than that chosen in b, continue.

j. Repeat step b for the B4-100 or B5-105.

k. Linearly interpolate based on the F_A/F determined in i to obtain corresponding P/D and 1/J.

l. Repeat steps c through e using the new values from k to determine a revised τ_C limit.

m. Calculate A_P using (6) and (7).

n. Determine the actual cavitation coefficient, τ_C, from (11). The value of q_T used in this calculation is that used in step l.

o. If τ_C from step n is less than or equal to τ_C from step l, η_{PO} can then be determined from Appendix A by interpolating based on the F_A/F. If τ_C is significantly below the required value it may be desirable to iterate as below to get closer to the 5% criteria. If τ_C is greater than the required value, continue.

p. Determine a new A_P required from

$$A_P = T/(q_T \ \tau_C)$$

where q_T is as in step n and τ_C is from step l.

q. Calculate A_D from (6).

r. Calculate a new minimum required expanded blade area ratio, F_A/F, as in step i.

s. Repeat steps k through o until a satisfactory solution is obtained.

The above procedure is somewhat tedious but it is relatively simple and has been included in the computer program.

This procedure provides the analyst with a propeller open water efficiency that includes an estimate for achieving an acceptable level of cavitation.

When utilizing the above for power plant selection analysis, first determine the propeller characteristics using the diameter constraint. If the propeller RPM is less than that which matches the RPM of the slow speed diesels under consideration, determine the propeller characteristics using the

RPM constraint. If the RPM determined from the diameter constraint is greater than that which matches the slow speed diesel, the above method cannot be used to determine the propeller characteristics for that plant. It will be necessary in that case to select a propeller which is not at an optimum match for the hull characteristics and the graphs in Appendix A were based on that match. It therefore becomes necesaary to utilize the graphical techniques used in reference 2. Instead of picking an optimal η_{PO}, the advance coefficient dictated by the diesel RPM and the propeller diameter (dictated by the hull) will determine the propeller characteristics. The propeller will necessarily not be at the optimum η_{PO}.

3.5 DETERMINING THE PROPULSION COEFFICIENT

As shown in reference 2, the propulsion coefficient is defined as

$$PC = \frac{EHP}{SHP}$$

where SHP is the output of the prime mover. It is also shown that

$$PC = \eta_{HULL} \; \eta_{PO} \; \eta_r \; \eta_{SHAFT}$$

where

$$\eta_{HULL} = \left(\frac{1-t}{1-w}\right)$$

η_{PO} = propeller open water efficiency

η_r = relative rotative efficiency

η_{SHAFT} = propeller shaft transmission efficiency

Typical values for η_r and η_{SHAFT} can be found in reference 3.

4. PROPULSION PLANT COSTS

The initial investment costs and significant annual operating costs associated with the ship power plant for single screw ships in the 10,000 SHP to 50,000 SHP range are developed. The plants considered are non-reheat and reheat steam, slow- and medium-speed diesels, and two types of gas turbine plants.

4.1 GENERAL

The SHP required determined by the procedure in Chapter 3 is based on an optimum match between the propeller and the hull. Ideally, a propulsion plant would be chosen with exactly that continuous power rating. In fact, that is not usually possible when considering on-the-shelf components available in the market place. A detailed design must consider matching the hull, the propeller, and the power plant. The economically optimum is likely to be a match which has both the propeller and power plant operating off of its component optimum. For the purposes of preliminary design, the functions developed herein approximate that there are plants available at each point in the power range (except for gas turbines). (See Sec. 3.a.) Cognizance is taken of limits on the maximum size single prime mover available (such as approximately 18,000 SHP for a single medium-speed diesel).

All costs have been adjusted to 1970 levels using a rate of inflation of 5% per year. No costs were adjusted for more than four years.

4.2 INITIAL INVESTMENT COSTS

Those initial investment costs directly attributed to the power plant, the shafting and the propeller are considered. They are the material acquisition and installation costs. They are combined into a single cost function for each plant.

Alterations to hull structure costs due to changes in power plant weight and fuel weight are omitted. As described in Chapter 2, those changes also involve changes in the hull configuration and thus the EHP required. Additionally, changes in the hull configuration will be a function of plant volume and configuration and not just a function of weight changes. One study (reference 7) concluded that a direct diesel plant had a 3% reduction in cargo volume from a steam plant of the same rated power. This represents a loss of 3% annual revenues. For a ship generating $3 million annual revenues, this is a loss of $90,000 per year. The difference in initial steel cost for the plants considered in reference 2 was $100,000. This shows that the ship-as-a-whole must be considered for this correction.

The costs obtained from Erichsen (reference 8) were based on the world market place and utilized a labor rate of $2.50 per manhour, a 70% overhead rate and a 5% profit on the total cost. This was considered the 1969 level. All investment costs were adjusted to those rates where possible and then set to the 1970 level.

4.2.1 Non-reheat Steam Plants

Cost functions were obtained from references 2, 8, and 9. A cost function was developed from the material acquisition and manhours for installation data in reference 10. There was good agreement over the entire power range between the Benford function from reference 8 and the Hewitt function. Benford was chosen because of the larger base of his study. The non-reheat steam plant initial cost is taken to be

$$IC_{STNR} = 5.502 \left(\frac{SHP}{1000.}\right)^{.6} \times 10^5 \qquad (\$)$$

4.2.2 Reheat Steam Plants

The cost information in reference 9 was the only one which distinguished between reheat and non-reheat plants. Although it was the oldest data (1965) and therefore considered less reliable for absolute values of cost, it is reasonable to assume that the ratio of initial investment costs for the two types are still valid. Therefore, the initial cost of the reheat steam plant is taken to be

$$IC_{STRH} = 1.07 \times IC_{STNR} \qquad (\$)$$

4.2.3 Slow Speed Diesel Plants

Cost functions were obtained from references 2, 8, and 9. A cost function was developed from the information in reference 10. There was good agreement between the SFI function from reference 8 and the Hewitt function. SFI was chosen because of the larger base for the study. The slow speed diesel direct drive initial cost is taken to be

$$IC_{DL} = 4.778 \left(\frac{SHP}{1000}\right)^{.63} \times 10^5 \qquad (\$)$$

4.2.4 Medium Speed Diesel Plants

Cost functions were obtained from references 2 and 9. A cost function was developed from the information in reference 10. Some information was also obtained from a representative of a major diesel manufacturer. The initial cost of the medium speed diesel plant is taken to be

$$IC_{DM} = 1.736 \left(\frac{SHP}{1000}\right)^{.8814} \times 10^5 \qquad (\$)$$

4.2.5 Gas Turbine Plants

There is a limited amount of information for this plant. Hewitt in reference 2 considers first and second generation aircraft derivative gas turbines and improved second generation gas turbines. A cost function was

developed from the information in reference 10 which closely agreed with Hewitt's function for first and second generation A/C gas turbines. From the data in reference 11, the first and second generation A/C gas turbine function corresponds to the Pratt-Whitney FT4 series and the improved second generation A/C gas turbine function corresponds to the General Electric LM-2500. The terminology used by Hewitt will be adopted for the remainder of this paper.

The initial investment cost of the first and second generation aircraft gas turbine plant is taken to be

$$IC_{GT} = 8.61 \left(\frac{SHP}{1000}\right)^{.442} \times 10^5 \qquad (\$)$$

and the initial investment cost for the improved second generation aircraft gas turbine plant is taken to be

$$IC_{GTIMP} = 6.017 \left(\frac{SHP}{1000}\right)^{.629} \times 10^5 \qquad (\$)$$

4.3 ANNUAL OPERATING COSTS

The annual operating costs developed are fuel cost, lube oil cost, maintenance and repair cost, manning cost, and outage costs.

4.3.1 Fuel Cost

The total annual fuel cost for a known operating profile can be found from

$$\text{FUEL COST/YEAR} = \sum_i (SFC_i \times SHP_i \times HOURS_i/YEAR \times COST/lb.) \quad (\$/year)$$

where the index i indicates different power levels and the corresponding fuel rates and operating times. For the preliminary design analysis of commerical cargo vessels, the operating profile is not considered because most operation is at the design power level.

Fuel rates as a function of plant power ratings at maximum continuous power for the steam and diesel plants are presented in Appendix J of reference 2. These have been approximated as follows:

Non-reheat Steam Plants

SHP $\leq$ 20000

$$SFC_{STNR} = .861 \left(\frac{SHP}{1000}\right)^{-.211} \qquad (lb/SHP - hr)$$

20000 > SHP

$$SFC_{STNR} = .572 \left(\frac{SHP}{1000}\right)^{-.074} \qquad (lb/SHP - hr)$$

Reheat Steam Plants

$$SFC_{STRH} = .493 \left(\frac{SHP}{1000}\right)^{-.059} \qquad (lb/SHP - hr)$$

Slow Speed Diesel Plants

$$SFC_{DL} = .433 \left(\frac{SHP}{1000}\right)^{-.055} \qquad (lb/SHP - hr)$$

The limit on available medium speed diesels is about 18000 SHP. Plants greater than this size require that two diesels be used with a single reduction gear and plants greater than 36000 SHP will require three diesels.

Medium Speed Diesel Plants

SHP $\leq$ 18000

$$SFC_{DM} = .455 \left(\frac{SHP}{1000}\right)^{-.057} \qquad (lb/SHP - hr)$$

18000 < SHP $\leq$ 36000

$$SFC_{DM} = .455 \left(\frac{SHP}{2000}\right)^{-.057} \qquad (lb/SHP - hr)$$

36000 < SHP

$$SFC_{DM} = .455 \left(\frac{SHP}{3000}\right)^{-.057} \qquad (lb/SHP - hr)$$

Fuel rate functions for the gas turbine plants were developed from manufacturers' brochures.

For the first and second generation A/C gas turbines, the largest unit

available has a continuous rating of 34,400 SHP with a compressor inlet air temperature of 59° F. and the smallest has a rating close to 20,000 SHP. Therefore, below 20,000 SHP a plant operating below rated power is required and a plant operating above 34,400 SHP will require the use of two prime movers driving a single reduction gear.

The improved second generation aircraft gas turbine plant has a maximum rated power of 19,200. For the power range considered, this requires using up to three prime movers to drive the single reduction gear and also requires consideration of off-design operation.

Consideration of the above leads to the following fuel rate functions for the gas turbine plants.

First and Second Generation Aircraft Gas Turbine Plants

$SHP \leq 20000$

$$SFC_{GT} = 1.335 \left(\frac{SHP}{1000}\right)^{-.324} \qquad (lb/SHP - hr)$$

$20000 < SHP \leq 34400$

$$SFC_{GT} = .846 \left(\frac{SHP}{1000}\right)^{-.171} \qquad (lb/SHP - hr)$$

$34400 < SHP \leq 40000$

$$SFC_{GT} = 1.335 \left(\frac{SHP}{2000}\right)^{-.324} \qquad (lb/SHP - hr)$$

$40000 < SHP$

$$SFC_{GT} = .846 \left(\frac{SHP}{2000}\right)^{-.171} \qquad (lb/SHP - hr)$$

Improved Second Generation Aircraft Gas Turbine Plants

$SHP \leq 19200$

$$SFC_{GTIMP} = .885 \left(\frac{SHP}{1000}\right)^{-.254} \qquad (lb/SHP - hr)$$

$19200 < SHP \leq 38400$

$$SFC_{GTIMP} = .885 \left(\frac{SHP}{2000}\right)^{-.254} \qquad (lb/SHP - hr)$$

$38400 < SHP$

$$SFC_{GTIMP} = .885 \left(\frac{SHP}{3000}\right)^{-.254} \qquad (lb/SHP - hr)$$

The fuel rates developed consider that the steam and diesel plants operate using Bunker C fuel oil (LHV of 17,500 Btu/lb.) and the gas turbines utilize marine diesel fuel oil (LHV of 18,500 Btu/lb.).

4.3.2 Lube Oil Cost

For preliminary analysis, only the lube oil costs for the diesel plants need to be determined. They are developed from the information in reference 2.

Slow Speed Diesel Plants

$$LOC_{DL} = \left(.043 \times \frac{COST\ (\$)}{GAL.\ CRANKCASE\ OIL} + .111 \times \frac{COST\ (\$)}{GAL.\ CYLINDER\ OIL}\right)$$

$$\times \left(\frac{SHP}{1000}\right) \times HOURS/YEAR \qquad (\$/YEAR)$$

Medium Speed Diesel Plants

$$LOC_{DM} = .33 \times \frac{COST\ (\$)}{GAL.\ MEDIUM\ OIL} \times \left(\frac{SHP}{1000}\right) \times \frac{HOURS}{YEAR} \qquad (\$/YEAR)$$

4.3.3 Maintenance and Repair Costs

Non-reheat Steam Plants. Maintenance costs were obtained from references 2, 8, and 9. Hewitt and SFI from reference 8 were in good agreement. The SFI costs are taken because of the size of the data base.

$$MC_{STNR} = 24560 + .98\ (SHP) \qquad (\$/YEAR)$$

Reheat Steam Plants. Based on the distinction in the Sharp Study between reheat and non-reheat plants, the reheat plant maintenance costs are taken to be

$$MC_{STRH} = 1.07 \times MC_{STNR}$$

Diesel Plants. The same references were available for the diesel plant as for the steam plant. No distinctions were made between slow and medium speed plants and they are therefore assumed to be the same. The results of the regression analysis performed by Erichsen are in reasonable agreement with Hewitt and they are taken because of the statistical confidence level determined.

$$\left.\begin{array}{l} MC_{DL} \\ \\ MC_{DM} \end{array}\right\} = 4.2 \times SHP \qquad (\$/YEAR)$$

Gas Turbine Plants. The maintenance costs are from reference 2.

$$\left.\begin{array}{l} MC_{GT} \\ \\ MC_{GTIMP} \end{array}\right\} = 3.47 \times SHP \qquad (\$/YEAR)$$

4.3.4 Manning Costs

Manning costs are developed in Appendix G of reference 2. The manning levels used are based on those of foreign flags for steam and diesel plants, and on the manning of the Euroliner, a containership powered by two FT4 engines, for gas turbines. The costs are shown in Table 1.

4.3.5 Outage Costs

Outage costs are a common method for accounting for plant reliability. The outage cost is the result of multiplying the days a ship loses a year due to power plant maintenance and casualties by the cost penalty per day. The cost penalty includes the additional port fees, towing fees, etc. (Note that the repair costs are already accounted for in the maintenance and repair costs.) Additionally, cognizance must be made of the difference between plants in the days at sea available per year when determining trips per year for calculation of the annual revenues.

TABLE 1. MANNING COSTS

	Steam Plant		Diesel Plant*		Gas Turbine Plant	
	No.	$/Year	No.	$/Year	No.	$/Year
Chief Engineer	1	16,970	1	16,970	1	16,970
1st. Asst. Engr.	1	11,500	1	11,500	1	11,500
2nd. Asst. Engr.	1	9,170	1	9,170	1	9,170
3rd. Asst. Engr.	1	8,540	1	8,540	1	8,540
Electrician	1	6,910	1	6,910	2	13,820
Diesel Machinist	-	--	2	14,750	-	--
Pumpman	1	6,760	1	6,760	1	6,760
Oiler	3	15,100	1	5,390	2	10,790
Wiper	3	14,990	1	4,990	-	--
TOTALS	12 men	89,940	9	84,980	9	57,550
Add 58.2% to Base Wage for Overtime & Benefits		142,300		134,400		91,000
Add 34% for Inflation		190,700		180,100		122,000
Manning Cost ($/Year)		0.191 million		0.180 million		0.122 million

*For SHP $\leq$ 30,000. Add 1 oiler and 1 wiper for SHP > 30,000.

Outage costs are calculated by

$$OC = (1 - \text{AVAILABILITY}) \times 365 \times \frac{\text{PENALTY COST (\$)}}{\text{DAY}} \qquad (\$/\text{YEAR})$$

The following are estimates of availability for the different plants developed from references 2, 7, 12, and 13.

PLANT TYPE	AVAILABILITY PER YEAR
Steam	.958
Slow speed diesel	.939
Medium speed diesel	.925
Gas turbine	.983

5. COMPUTER PROGRAM: PRELIMINARY POWER PLANT EVALUATION AIDE

The computer program developed to assist in preliminary design stage power plant selection is described. Its input-output features are presented.

5.1 THE PROGRAM

5.1.1 General

A computer program has been developed which utilizes the procedures described in Chapter 3 to determine propeller characteristics based on the diameter constraint and the RPM constraint. It uses the data from reference 6 for the Wageningen B-Screw series for four and five bladed propellers. An approximation to the 5% back cavitation criteria is applied. The propulsion coefficient and the required plant power rating, SHP, are calculated. The initial investment costs and annual fuel costs, lube oil costs, maintenance and repair costs, and manning costs are determined utilizing the power rating from the propeller calculation and the cost functions developed in Chapter 4. Applying the present value technique, the present value of the annual costs are calculated and then added to the initial investment costs to determine the total present value of the costs directly associated with each propulsion plant.

5.1.2 Determination of the Propeller Characteristics and the Propulsion Plant Power Rating (SHP)

The graphs which present η_{PO}, P/D ratio, and 1/J as a function of K_T/J^2 and K_T/J^4 presented in Appendix A have been approximated by combinations of the parabolic equation

$$y = A x^2 + B x + C$$

and the straight line equation

$$y = M x + B$$

The approximations developed are presented in Appendix B.

The 5% back cavitation criterion approximated in Figure 5 is considered satisfied if the cavitation index, τ_C, calculated from the propeller loading and propeller characteristics is within 10% of the 5% line at the calculated value of the cavitation number, $\sigma_{0.7R}$. This is illustrated in Figure 5.

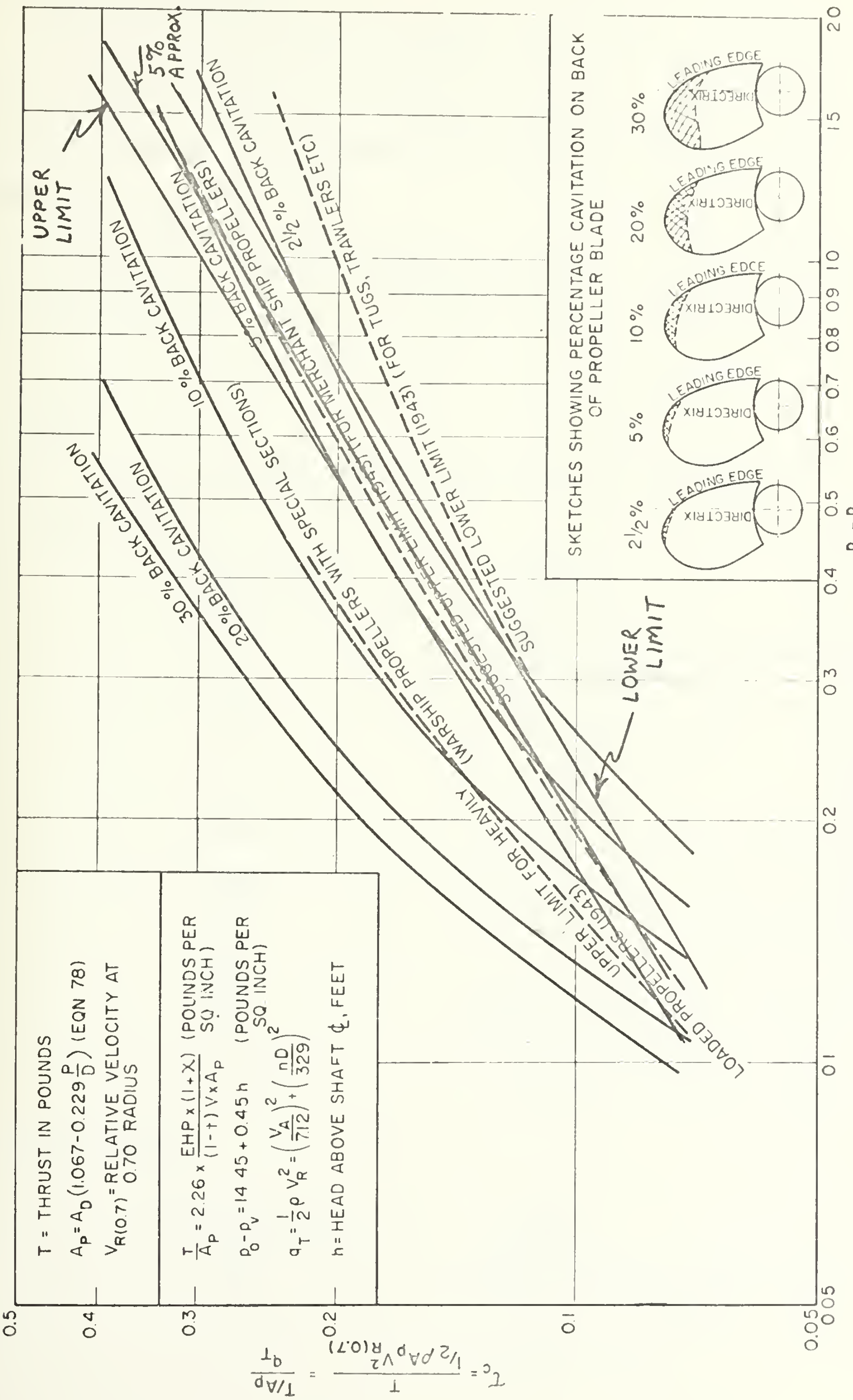
The first propeller calculation is based on the diameter constraint and uses the procedure from Chapter 3 to obtain a satisfactory solution. If the RPM input for the slow speed diesel is greater than 1.1 times the RPM determined from the diameter constraint solution, an RPM constraint solution is obtained for the slow speed diesel. The approximations in Appendix B for the four bladed series are utilized for both the four and five bladed solution to the RPM constraint. If the RPM from the diameter constraint solution is within plus or minus 10 revolutions per minute of the diesel RPM, the propeller characteristics of the slow speed diesel are taken to be the same as previously determined, and if it is greater than the diesel RPM plus 10 revolutions per minute, no propeller calculation is performed for the slow speed diesel. In the latter case, the economic parameters for the slow speed diesel are set to zero.

The power plant size for both propellers (as appropriate) are determined using the formula for the propulsion coefficient from Chapter 3.

5.1.3 Determination of Costs

The calculation of costs is a straight-forward application of the cost functions determined in Chapter 4.

Figure 5. Cavitation Criterion for Computer Program



5.1.4 Weight/Availability

The weight functions from reference 2 (all straight-line functions dependent on SHP) have been included in the program. The availability factors from Chapter 4 are also part of the printed output.

5.2 PROGRAM INPUT-OUTPUT

The program is written in FORTRAN IV, Level G-1, for use on the IBM Model 370/165 Digital Computer. A program listing is included in Appendix C.

5.2.1 Input

The required input parameters and format are given below.

Card 1 (FORMAT 8F10.3)

COLUMN	VARIABLE NAME	REMARKS
1-10	EHP	Effective horsepower (bare hull and appendages)
11-20	VKTS	Ship speed (knots)
21-30	THFAC	(1 - t)
31-40	WKFAC	(1 - w)
41-50	DENS	Density of water (lb-sec^2/ft^4)
51-60	DIA	Propeller diameter (feet)
61-70	HGT	Head of water at propeller centerline (feet)
71-80	ETAR	η_R (relative rotative efficiency)

Card 2 (FORMAT 8F10.3)

COLUMN	VARIABLE NAME	REMARKS
1-10	ETASH	η_{SHAFT} (propeller shaft transmission efficiency)
11-20	XINT	Discount rate

COLUMN	VARIABLE NAME	REMARKS
21-30	BKCCST	Cost of Bunker C Fuel Oil (S/barrel)
31-40	DCKLC	Cost of Slow Speed Diesel Crankcase Oil ($/gallon)
41-50	DCYLC	Cost of Slow Speed Diesel Cylinder Oil ($/gallon)
51-60	DMCST	Cost of Marine Diesel Fuel Oil ($/barrel)
61-70	DLCST	Cost of Medium Speed Diesel Lube Oil ($/gallon)
71-80	HOURS	Hours/year of plant operation

Card 3 (FORMAT 2F10.3, 3I4)

COLUMN	VARIABLE NAME	REMARKS
1-10	RPMD	RPM of Slow Speed Diesel
11-20	ETASHD	η_{SHAFT} Direct Drive Diesel (Slow speed) Plant
21-23		Leave blank
24	NBLAD	Number of blades for propeller (must be 4 or 5)
25-28	IYRS	Number of years the ship is to operate (i.e., the economic life)
29-31		Leave blank
32	KSTOP	Index for computer exit. Leave blank if more data sets follow. Set at 1 if last (or only) data set.

5.2.2 Output

An example of the standard computer output is shown in Table 2. The diameter and RPM constraints are of the form $\sqrt{K_T/J^2}$ and $\sqrt{K_T/J^4}$.

```
                                    INPUT
EHP  = 12400.0  DEN    = 1.990  (1-T) =  0.828  DCKLC = $ 1.30  BKCCST = $ 3.98
DIA  =    26.4  ETAR   = 1.020  (1-W) =  0.725  DCYLC = $ 1.30  INTER  =   0.19
HGT  =    19.6  ETASH  = 1.000  RPMD  =   94.0  DLCST = $ 1.30  HOURS  =  7440.
VKTS =    18.6  ETASHD = 1.000  NBLAD =      4  DMCST = $ 5.79  YEARS  =     23

                         PROPELLER PARAMETERS
EFFIC. = 0.66480 ADV.COEF. = 0.78    RPM           =  66.5     CAV.NUM. = 0.72
P/D    = 1.19    FAF       = 0.57    DIA.CONSTR. = 0.601      TAUC     = 0.23
                       SLOW SPEED DIESEL PROPELLER
EFFIC. = 0.62576 ADV.COEF. = 0.65    DIAMETER      = 22.49     CAV.NUM. = 0.52
P/D    = 0.95    FA/F      = 0.64    RPM CONSTR. =  1.09      TAUC     = 0.19

            PLANT/SHAFT                          SLOW DIESEL PLANT/SHAFT
SHP = 16011.7       PROP.COEF. = 0.77    SHP = 17010.6      PROP.COEF. = 0.73
```

ECONOMIC PARAMETERS

	STEAM		DIESEL		GAS TURBINE	
	REHEAT	NON-REHEAT	SLOW SPEED	MEDIUM SPEED	A/C DERIV.	IMP. A/C DERIV.
INVESTMENT	$ 3108610.	$ 2905244.	$ 2848391.	$ 2000508.	$ 2933351.	$ 3443267.
ANNUAL COSTS						
MAINTENANCE	$ 43069.	$ 40251.	$ 71445.	$ 67249.	$ 55561.	$ 55561.
FUEL OIL	599606.	686986.	563848.	556467.	1260888.	1014961.
LUBE OIL	0.	0.	25337.	51105.	0.	0.
MANNING	190600.	190600.	180100.	180100.	122000.	122000.
TOTAL ANNUAL COSTS	$ 833275.	$ 917837.	$ 840730.	$ 854921.	$ 1438448.	$ 1192521.
PRESENT VALUE ANNUAL COSTS	$ 4305403.	$ 4742323.	$ 4343923.	$ 4417246.	$ 7432241.	$ 6161573.
PRESENT VALUE TOTAL COSTS	$ 7414013.	$ 7647567.	$ 7192314.	$ 6417754.	$ 10365592.	$ 9604840.
WEIGHT(TONS)	784.	784.	1351.	790.	460.	460.
AVAILABILITY	0.958	0.958	0.939	0.925	0.983	0.983

Table 2. Sample Computer Output

There are several messages that will be printed if there are difficulties encountered in execution of the program. They are:

(1) If $\sqrt{K_T/J^2} < .4$ or > 3.6 the message "DIAMETER CONSTRAINT OUTSIDE LIMITS DC = " will be printed.

(2) If NBLAD input was not four or five, the message "NBLAD NOT ACCEPTABLE" will be printed.

(3) If the blade area ratio, F_A/F, required is calculated to be greater than 1.00 when NBLAD equals four or greater than 1.05 when NBLAD equals five, the message "F_A/F OUTSIDE LIMITS F_A/F = " will be printed.

(4) If τ_C will not converge to the acceptable range in five iterations, the message "CAVITATION INDEX WILL NOT CONVERGE IN 5 ITERATIONS TAUC3 = TAUC2 = TAUC2L = " will be printed where

TAUC3 = the calculated propeller cavitation index

TAUC2 = the upper limit for the cavitation index

TAUC2L = the lower limit for the cavitation index.

If (1) through (4) occur, the program will go to the next data set. If the diameter constraint solution is obtained without difficulty but there are problems with the RPM solution, an error message similar to (1) through (4) will be printed, the slow speed diesel economic parameters will be set to zero and the other economic parameters determined.

6. RESULTS

The results of the computer program solutions are presented and discussed. The propeller characteristics that the program develops are presented first and then the results of the economic calculations are shown.

6.1 PROPELLER CHARACTERISTICS

The objective of this section is to determine the reasonableness of the computer program as a predictor of propeller open water efficiency. The computer results are compared to other calculations.

The sample propeller calculation shown on page 421 of reference 3 is compared to computer results:

INPUT

EHP = 13000

V = 21 knots

Diameter = 21.0 feet

Shaft Centerline = 24.0 feet

$\eta_r = 1.05$

$\eta_{SHAFT} = 1.0$

$(1-t) = 0.85$

$(1-w) = 0.80$

5% back cavitation criterion

RESULTS

PNA	COMPUTER PROGRAM
$P/D = 1.135$	$P/D = 1.25$
$\eta_{PO} = 0.675$	$\eta_{PO} = 0.663$
$F_A/F = 0.624$	$F_A/F = 0.680$

The program η_{PO} is 1.2% less than the PNA graphical solution. Several graphical solutions utilizing the same diameter or RPM constraints were performed on both the older Troost curves and the updated curves from reference 6. In all cases, the solution from the updated curves gave an η_{PO} from 1% to 2% less than the η_{PO} from the older curves. The above example is therefore well within those limits. The same problem carried out graphically on the updated curves gave the same results as the computer program, thus checking the program modelling of the curves from reference 6 when using the diameter constraint.

Examination of several problems showed that the difference in η_{PO} for the diameter constraint and RPM constraint (the slow speed diesel calculation) solutions was not 3.5% for each 10 revolutions per minute that was predicted by Sharp in reference 9. One of Sharp's references was the work of Hadler, Stuntz, and Pien (reference 14). This was a systematic study of the effects of propeller diameter, block coefficient, displacement and trim upon the propulsion coefficient for the Series - 60 hull forms. For purposes of comparison, the combinations that Sharp extracted were run on the computer. The results are presented in Table 3. The Troost results are from reference 14 and are the ones shown in Sharp (reference 9).

The results for a block coefficient of 0.60 illustrate a major difference in calculations. The F_A/F from reference 14 "were selected on the basis of current design practice and checked for cavitation by Lerbs data" (page 125, reference 14). There is no elaboration. However, the Lerbs criterion is less restrictive than the 5% back cavitation criterion and partially explains the lower F_A/F.

TABLE 3. PROPELLER CHARACTERISTICS

BLOCK COEFFICIENT = .60

PROP. DIA.(ft)		21.36	22.40	25.6
TROOST	P/D	1.046	1.040	1.000
	F_A/F	.616	.550	.400
	η_{PO}	61.8	63.5	69.4
	RPM	131.6	120.0	101.6
COMPUTER	P/D	*	*	1.28
	F_A/F			.99
	η_{PO}			62.0
	RPM			82.6

BLOCK COEFFICIENT = .65

PROP. DIA.(ft)		21.36	23.20	26.40
TROOST	P/D	1.040	1.080	1.060
	F_A/F	.605	.525	.413
	η_{PO}	63.0	66.8	71.0
	RPM	109.9	94.2	79.5
COMPUTER	P/D	1.14	1.19	1.28
	F_A/F	.79	.72	.64
	η_{PO}	61.3	63.9	67.8
	RPM	103.6	89.3	70.7

BLOCK COEFFICIENT = .70

PROP. DIA.(ft)		22.0	24.0	26.4
TROOST	P/D	1.090	1.080	1.056
	F_A/F	.564	.500	.456
	η_{PO}	61.5	66.0	68.3
	RPM	94.0	81.2	71.6
COMPUTER	P/D	1.08	1.13	1.19
	F_A/F	.68	.63	.57
	η_{PO}	60.9	63.6	66.5
	RPM	92.8	79.2	66.5

*F_A/F required too large.

Allowing for the difference in F_A/F and for the 1% to 2% difference for the updated curves, there is reasonable agreement in the open water efficiencies. The computer results were obtained from the diameter constraint solution. The results of some RPM constraint solutions are shown below for the 0.65 and 0.70 block coefficients (C_B).

$C_B = 0.65$	$C_B = 0.70$
RPM = 109.9	RPM = 94.0

RESULTS

Diameter = 21.24 feet	Diameter = 22.51
P/D = 0.95	P/D = 0.95
F_A/F = 0.75	F_A/F = 0.63
η_{PO} = 0.624	η_{PO} = 0.627

The RPM input was set for the Troost results of the smaller propeller for each block coefficient as seen in Table 2. The calculation for C_B = 0.70 was checked with a graphical solution using the updated curves, thus checking the RPM constraint modelling of the curves in reference 6. Comparison with the Troost results and the computer results determined in Table 3 indicates some improvement in the η_{PO} from the RPM constraint solution at the specified RPM.

For the 0.65 block coefficient, graphical solutions were performed on the older Troost curves using the diameter constraint (diameter - 21.36 feet) and the RPM constraint (RPM - 109.9). The diameter solution agreed with that in Table 3. The RPM solution gave an η_{PO} approximately 1% higher. This thus supports the trend exhibited by the computer results.

It is reasonable to conclude that the results from reference 14 are based on optimum η_{PO} for the given diameter but it is wrong to conclude that

they are the optimum efficiencies for the given RPM.

The results shown in Table 4 are based on the input parameters used by Dow and Luckard in reference 15. They utilized the propeller design program developed by Kroeger in reference 16. The η_{PO} from that effort was 0.675, or 0.067 higher than predicted by the program developed herein. The Kroeger program is based on more modern aerfoil-type propellers.

On the basis of the above results, it is concluded that the program is a reasonable predictor of η_{PO} for the Wageningen B Screw Series modeled. It also appears that the rule-of-thumb proposed by Sharp is subject to question. Application of the RPM constraint and the 5% back cavitation criterion by both the computer program and graphical solution has resulted in propellers which meet all constraints but do not show the 3.5% loss for each 10 RPM. It is realized that the above sample is not sufficient to reach a definite conclusion. It is reasonable, however, to conclude that such a rule-of-thumb should be used with care. It would be better to actually determine the η_{PO} based on the given diameter and RPM constraints, the chosen cavitation criterion, and the chosen propeller curves. Additionally, it is wrong to conclude that an η_{PO} determined from a diameter constraint solution is the optimum η_{PO} for the resultant RPM from that solution. A separate solution based on the RPM constraint must be performed to obtain the optimum η_{PO} for the specified RPM.

6.2 ECONOMIC PARAMETERS

The purpose of this section is to examine the economic results of three representative problems. The computer outputs for these problems are in Tables 4, 5, and 6. They are based on past problems from MIT subject offerings 13.21 and 13.22.

```
                                       INPUT
EHP  = 14000.0  DEN    = 1.990  (1-T) =  0.830  DCKLC = $ 1.03  BKCCST = $ 3.45
DIA  =    23.0  ETAR   = 1.050  (1-W) =  0.660  DCYLC = $ 1.68  INTER  =   0.19
HGT  =    18.5  ETASH  = 0.980  RPMD  =  100.0  DLCST = $ 1.31  HOURS  =  7440.
VKTS =    20.0  ETASHD = 1.000  NBLAD =      4  DMCST = $ 5.01  YEARS  =     23

                             PROPELLER PARAMETERS
EFFIC. = 0.60757 ADV.COEF. = 0.67    RPM           =  86.8    CAV.NUM. = 0.57
P/D    = 1.08    FAF       = 0.69    DIA.CONSTR. = 0.723     TAUC     = 0.20
                        SLOW SPEED DIESEL PROPELLER
EFFIC. = 0.60413 ADV.COEF. = 0.60    DIAMETER      = 22.23    CAV.NUM. = 0.46
P/D    = 0.91    FA/F      = 0.67    RPM CONSTR. =  1.24     TAUC     = 0.17

           PLANT/SHAFT                           SLOW DIESEL PLANT/SHAFT
SHP = 17806.6      PROP.COEF. = 0.79    SHP = 17549.9      PROP.COEF. = 0.80
```

ECONOMIC PARAMETERS

	STEAM		DIESEL		GAS TURBINE	
	REHEAT	NON-REHEAT	SLOW SPEED	MEDIUM SPEED	A/C DERIV.	IMP. A/C DERIV.
INVESTMENT	$ 3313238.	$ 3096485.	$ 2904947.	$ 2196906.	$ 3074395.	$ 3681250.
ANNUAL COSTS						
MAINTENANCE	$ 44951.	$ 42010.	$ 73709.	$ 74788.	$ 61789.	$ 61789.
FUEL OIL	574412.	647577.	503391.	533199.	1172275.	950675.
LUBE OIL	0.	0.	30132.	57272.	0.	0.
MANNING	190600.	190600.	180100.	180100.	122000.	122000.
TOTAL ANNUAL COSTS	$ 809963.	$ 880187.	$ 787333.	$ 845358.	$ 1356063.	$ 1134464.
PRESENT VALUE ANNUAL COSTS	$ 4184956.	$ 4547794.	$ 4068026.	$ 4367836.	$ 7006570.	$ 5861602.
PRESENT VALUE TOTAL COSTS	$ 7498194.	$ 7644279.	$ 6972973.	$ 6564742.	$ 10080965.	$ 9542852.
WEIGHT(TONS)	823.	823.	1377.	862.	487.	487.
AVAILABILITY	0.958	0.958	0.939	0.925	0.983	0.983

Table 4. Computer Output - 14000 EHP Hull

Table 5. Computer Output - 19200 EHP Hull

```
                                  INPUT
EHP  = 19200.0  DEN    = 1.990  (1-T) =   0.800  DCKLC = $ 1.30  BKCCST = $ 3.98
DIA  =    26.0  ETAR   = 1.050  (1-W) =   0.580  DCYLC = $ 1.30  INTER  =   0.19
HGT  =    24.0  ETASH  = 0.980  RPMD  =   100.0  DLCST = $ 1.30  HOURS  =  7440.
VKTS =    16.0  ETASHD = 1.000  NBLAD =       4  DMCST = $ 5.79  YEARS  =     23

                          PROPELLER PARAMETERS
EFFIC. = 0.44944 ADV.COEF. = 0.41    RPM          =  88.1    CAV.NUM. = 0.59
P/D    = 0.87    FAF       = 0.78    DIA.CONSTR. = 1.213    TAUC     = 0.19
                        SLOW SPEED DIESEL PROPELLER
EFFIC. = 0.44944 ADV.COEF. = 0.36    DIAMETER     = 25.97    CAV.NUM. = 0.39
P/D    = 0.71    FA/F      = 0.74    RPM CONSTR. =  3.35    TAUC     = 0.15

           PLANT/SHAFT                          SLOW DIESEL PLANT/SHAFT
SHP = 30099.0       PROP.COEF. = 0.64   SHP = 29497.0     PROP.COEF. = 0.65
```

ECONOMIC PARAMETERS

	STEAM		DIESEL		GAS TURBINE	
	REHEAT	NON-REHEAT	SLOW SPEED	MEDIUM SPEED	A/C DERIV.	IMP. A/C DERIV.
INVESTMENT	$ 4539781.	$ 4242788.	$ 4029079.	$ 3489353.	$ 3877240.	$ 5121405.
ANNUAL COSTS						
MAINTENANCE	$ 57841.	$ 54057.	$ 123887.	$ 126416.	$ 104444.	$ 104444.
FUEL OIL	1085944.	1197232.	948574.	1049754.	2061037.	1938208.
LUBE OIL	0.	0.	43935.	96069.	0.	0.
MANNING	190600.	190600.	180100.	202200.	122000.	122000.
TOTAL ANNUAL COSTS	$ 1334384.	$ 1441889.	$ 1296496.	$ 1474437.	$ 2287480.	$ 2164651.
PRESENT VALUE ANNUAL COSTS	$ 6894558.	$ 7450020.	$ 6698796.	$ 7618190.	$ 11819059.	$ 11184421.
PRESENT VALUE TOTAL COSTS	$ 11434339.	$ 11692808.	$ 10727875.	$ 11107543.	$ 15696299.	$ 16305826.
WEIGHT(TONS)	1087.	1087.	1975.	1354.	671.	671.
AVAILABILITY	0.958	0.958	0.939	0.925	0.983	0.983

```
                                      INPUT
EHP  = 28000.0  DEN    = 1.990  (1-T) =  0.800  DCKLC = $ 1.30  BKCCST = $ 3.98
DIA  =    31.0  ETAR   = 1.050  (1-W) =  0.580  DCYLC = $ 1.30  INTER  =   0.19
HGT  =    26.4  ETASH  = 0.980  RPMD  =  100.0  DLCST = $ 1.30  HOURS  =  7440.
VKTS =    16.0  ETASHD = 1.000  NBLAD =      5  DMCST = $ 5.79  YEARS  =     23

                              PROPELLER PARAMETERS
EFFIC. = 0.44592 ADV.COEF. = 0.42    RPM            =  72.2    CAV.NUM. = 0.55
P/D    = 0.86    FAF       = 0.82    DIA.CONSTR. = 1.229    TAUC     = 0.19
                            SLOW SPEED DIESEL PROPELLER
EFFIC. = 0.43151 ADV.COEF. = 0.33    DIAMETER       = 28.56    CAV.NUM. = 0.34
P/D    = 0.69    FA/F      = 0.76    RPM CONSTR. =   4.04    TAUC     = 0.15

              PLANT/SHAFT                         SLOW DIESEL PLANT/SHAFT
SHP = 44240.8       PROP.COEF. = 0.63    SHP = 44804.3      PROP.COEF. = 0.62
```

ECONOMIC PARAMETERS

	STEAM		DIESEL		GAS TURBINE	
	REHEAT	NON-REHEAT	SLOW SPEED	MEDIUM SPEED	A/C DERIV.	IMP. A/C DERIV.
INVESTMENT	$ 5720020.	$ 5345815.	$ 5242967.	$ 4899794.	$ 4596808.	$ 6525331.
ANNUAL COSTS						
MAINTENANCE	$ 72670.	$ 67916.	$ 188178.	$ 185811.	$ 153516.	$ 153516.
FUEL OIL	1560305.	1710296.	1408083.	1544762.	3193224.	2863597.
LUBE OIL	0.	0.	66735.	141206.	0.	0.
MANNING	190600.	190600.	202200.	202200.	122000.	122000.
TOTAL ANNUAL COSTS	$ 1823575.	$ 1968811.	$ 1865196.	$ 2073978.	$ 3468739.	$ 3139112.
PRESENT VALUE ANNUAL COSTS	$ 9422133.	$ 10172545.	$ 9637182.	$ 10715927.	$ 17922432.	$ 16219312.
PRESENT VALUE TOTAL COSTS	$ 15142153.	$ 15518360.	$ 14880149.	$ 15615721.	$ 22519232.	$ 22744640.
WEIGHT(TONS)	1391.	1391.	2740.	1920.	884.	884.
AVAILABILITY	0.958	0.958	0.939	0.925	0.983	0.983

Table 6. Computer Output - 28000 EHP Hull

Once the propeller η_{PO} is determined, the PC is established. The input for η_{SHAFT} to be used for all of the geared drive plants was 0.98 and for the direct drive diesel it was assumed to be 1.0. This is based on the assumption that most of the shaft losses are friction losses in the reduction gear and that only a small portion are losses in the stern tube. This assumption and the propeller results discussed in the previous section will not put the slow speed diesel at the disadvantage that it was given in reference 9.

The three problems illustrate the effect that plant size has on the economic parameters. The smaller plant in Table 4 shows significant advantages for the medium speed diesel. Both diesel plants are more economical for the costs considered than the steam plants. The mid-sized plant in Table 5 favors the slow speed diesel with the medium speed diesel and both steam plants essentially the same. The larger plant in Table 6 favors the slow speed diesel with the reheat steam reasonably close. The gas turbine plants in all cases appear to be uneconomical. This is primarily due to the higher fuel consumption and the higher fuel costs.

The dominance of fuel costs in the annual costs is clearly demonstrated in all cases with manning costs next in importance.

The error that can be made if plant selection is not made on the ship-as-a-whole basis can be easily demonstrated. Assume there is a 3% reduction in cargo capacity for the diesel plant ship, and a revenue of $3M per year for the steam plant ship based on $300,000 per trip, 10 trips per year and 36 days per trip. The lost revenue for the diesel ship based on an equal number of trips per year is $90,000 per year. Next, consider the direct outage cost for each plant. Assuming a penalty of $50,000 per day, the

outage cost for the slow speed diesel ship is $1,114,000 per year and is $766,000 per year for the steam plant ship. Now the difference in revenue due to the outage must be considered. The diesel ship loses 22.3 days per year, 0.62 trips per year and $180,000 per year (0.62 trips per year x $291,000 per trip). The steam ship loses 15.3 days per year, 0.425 trips per year, and $127,500 per year (0.425 trips per year x $300,000 per trip). Therefore, the net penalty per year for the slow speed diesel ship when compared to the reheat steam ship is

$$(\$1,114,000 - \$766,000) + \$90,000 + (180,000 - \$127,500)$$

$$= \$470,500 \text{ per year}$$

The present value at the same rate and period as the other costs is $2.3M. When added to the total present value in Table 6, the selection of the economical plant shifts to the steam plant. Consideration of the lost revenue due only to lost cargo, $90,000 per year with a present value of $465,000, is by itself sufficient to make the steam plant competitive.

Because of the above discussion and the design sequence described in Chapter 2, no attempt is made to draw conclusions on which plants are most economical. Rather, it is concluded that a usable economic model has been developed as a computer program based on the cost functions described in Chapter 4 for the significant annual costs and investment costs. Additionally, availability factors are provided to be used for determination of outage costs and lost revenue.

The model can be used in several ways. Only a few are now suggested. They are (1) to determine the effect of discount rate on the total present value and relative ranking, (2) to determine the effect of changes in the

fuel and lube oil costs, (3) to determine the effect of changes in ship speed and thus power requirements and trips per year, and (4) to determine the effect of changes in the estimated life of the ships. Certainly there are other variations.

7. CONCLUSIONS AND RECOMMENDATIONS

The principal conclusions of this paper are:

(1) It is possible to construct a relatively simple model of propeller characteristics that can be utilized to match propeller and hull and to establish the propeller open water efficiency for design analysis. Such a model has been developed and a computer program written. It is based on a 5% back cavitation criterion and the Wageningen B-Screw Series data from reference 6.

(2) A computer model for determining propulsion plant initial investment costs and significant annual costs for reheat and non-reheat steam plants, for slow and medium speed diesel plants and for two gas turbine plants has been developed. The model is based on data gathered from several sources. It must be recognized that cost information is generally proprietary and that it is therefore difficult to obtain current and accurate information. Before major investment decisions are made, a ship owner or financial manager would be well advised to confirm specific results produced from a model such as developed herein.

(3) A preliminary design sequence has been described which requires power plant selection to be based on the evaluation of the ship-as-a-whole. Economic evaluation criteria and some simple calculations are combined to illustrate the requirement for this approach.

(4) It was demonstrated that the propeller open water efficiency determined from the diameter constraint is not necessarily the optimum for the resultant RPM. That must be determined from the RPM constraint solution.

The principal recommendations of this paper are:

(1) The effect of Reynolds number and propeller roughness on the propeller open water efficiency should be examined to determine if they can accurately be predicted for preliminary design analysis. The data in reference 6 is corrected to be consistent with smooth model propellers at the model Reynolds number. The information in reference 17 shows that for larger propellers and thus larger Reynolds number the η_{PO} increases but that with increased relative roughness the η_{PO} decreases. These effects should be examined further.

(2) Continued efforts are needed to better determine the economic costs so that valid economic comparisons can be made.

(3) There is a reasonable amount of data available on propulsion plant weights, but there is very little available on plant volumes for use in preliminary design estimates. Such volume data would be very useful and should be developed.

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APPENDICES

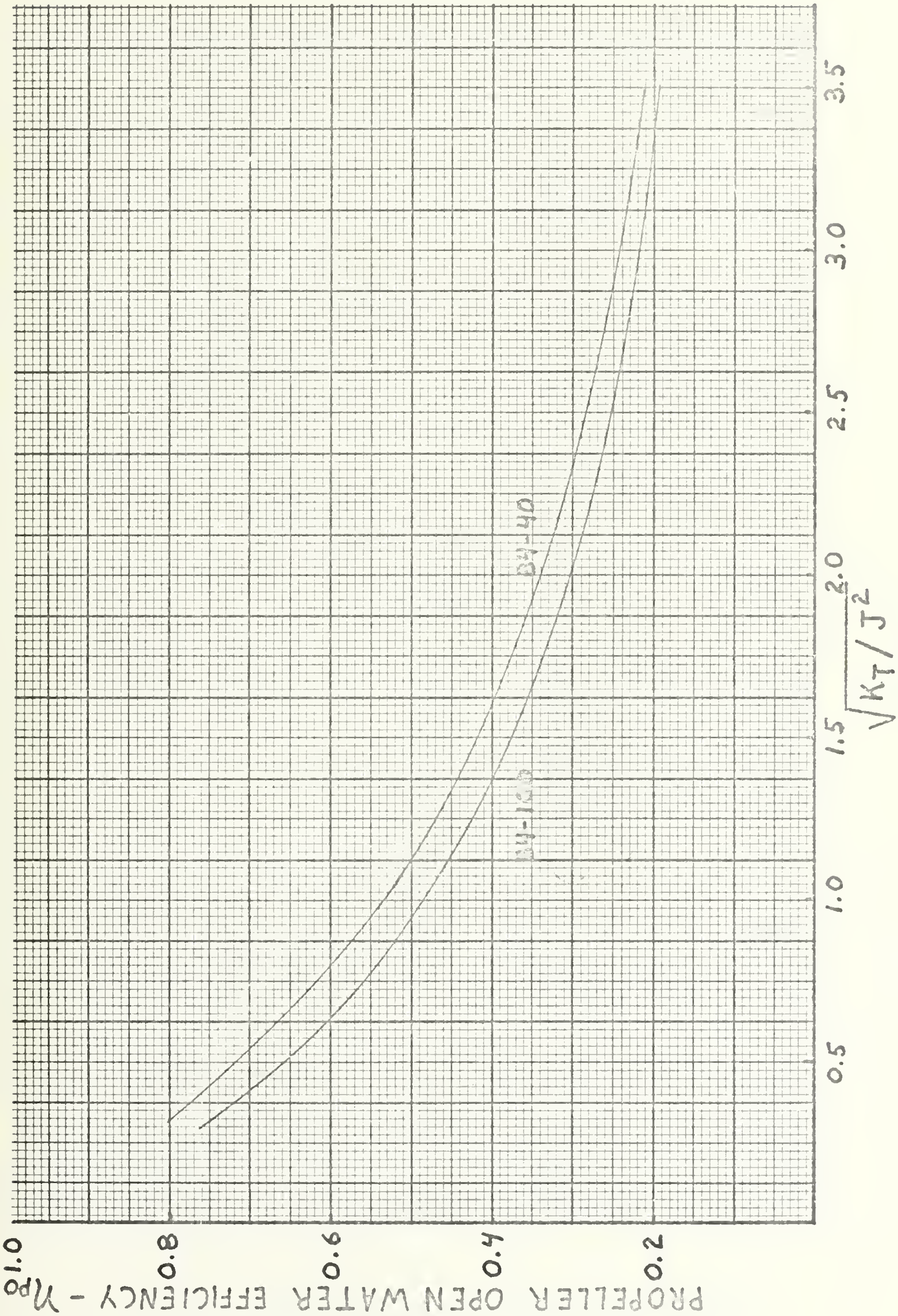
APPENDIX A.

PROPELLER CHARACTERISTIC CURVES;

WAGENINGEN B4 AND B5 SERIES

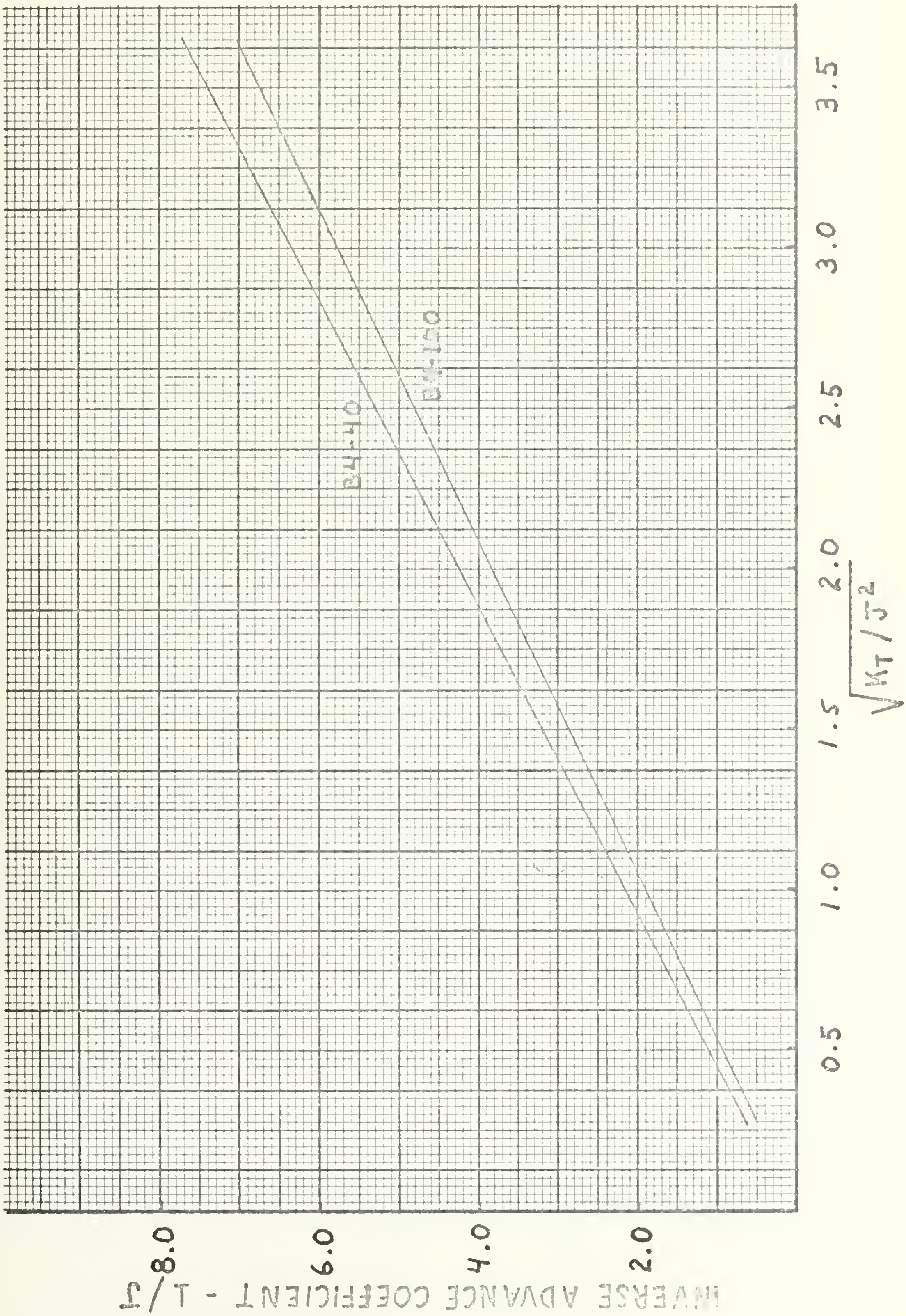
WAGENINGEN Four Bladed B-Screw Series:

Optimum Efficiency for Diameter Constraint



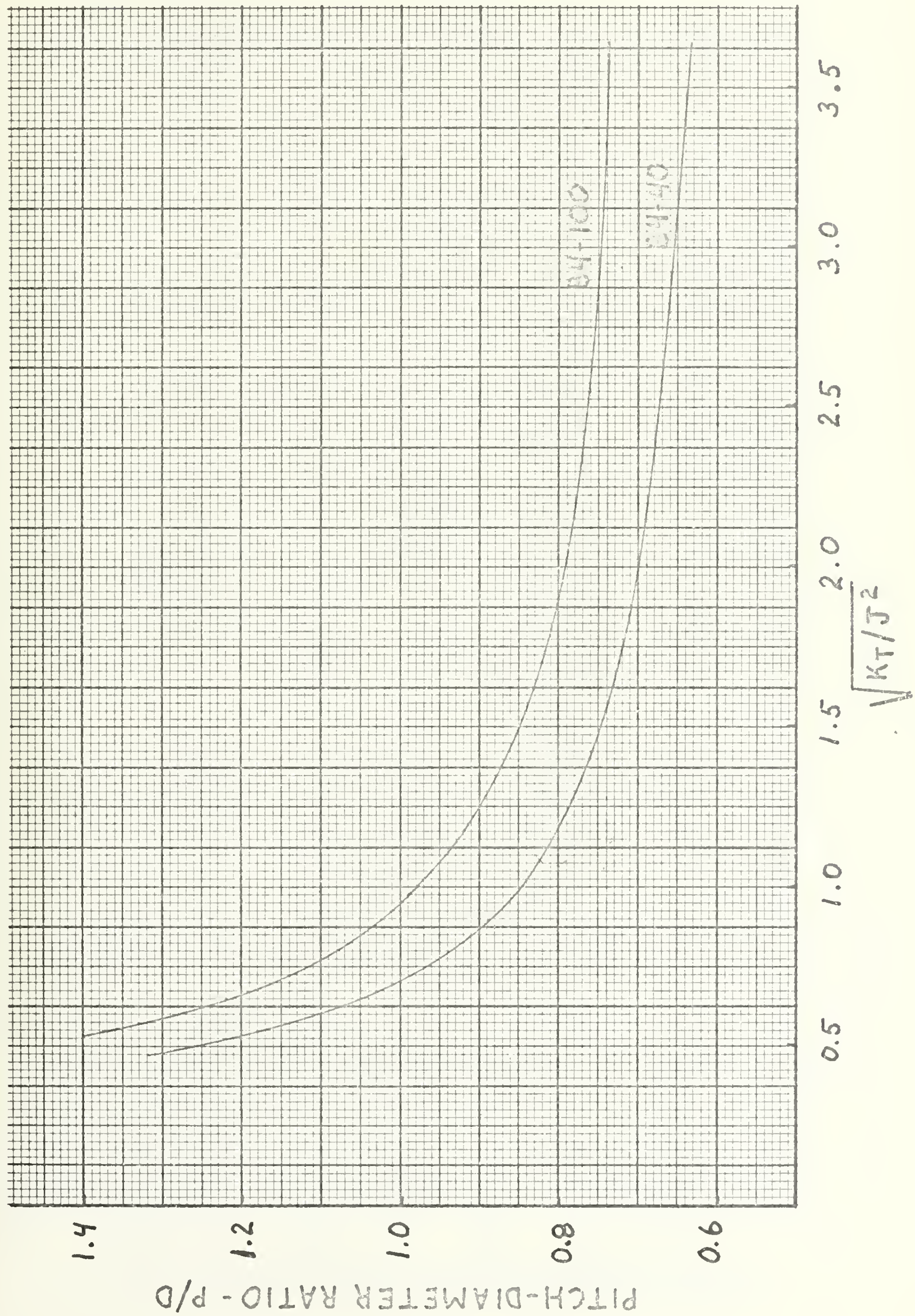
WAGENINGEN Four Bladed B-Screw Series:

Optimum Advance Ratio for Diameter Constraint



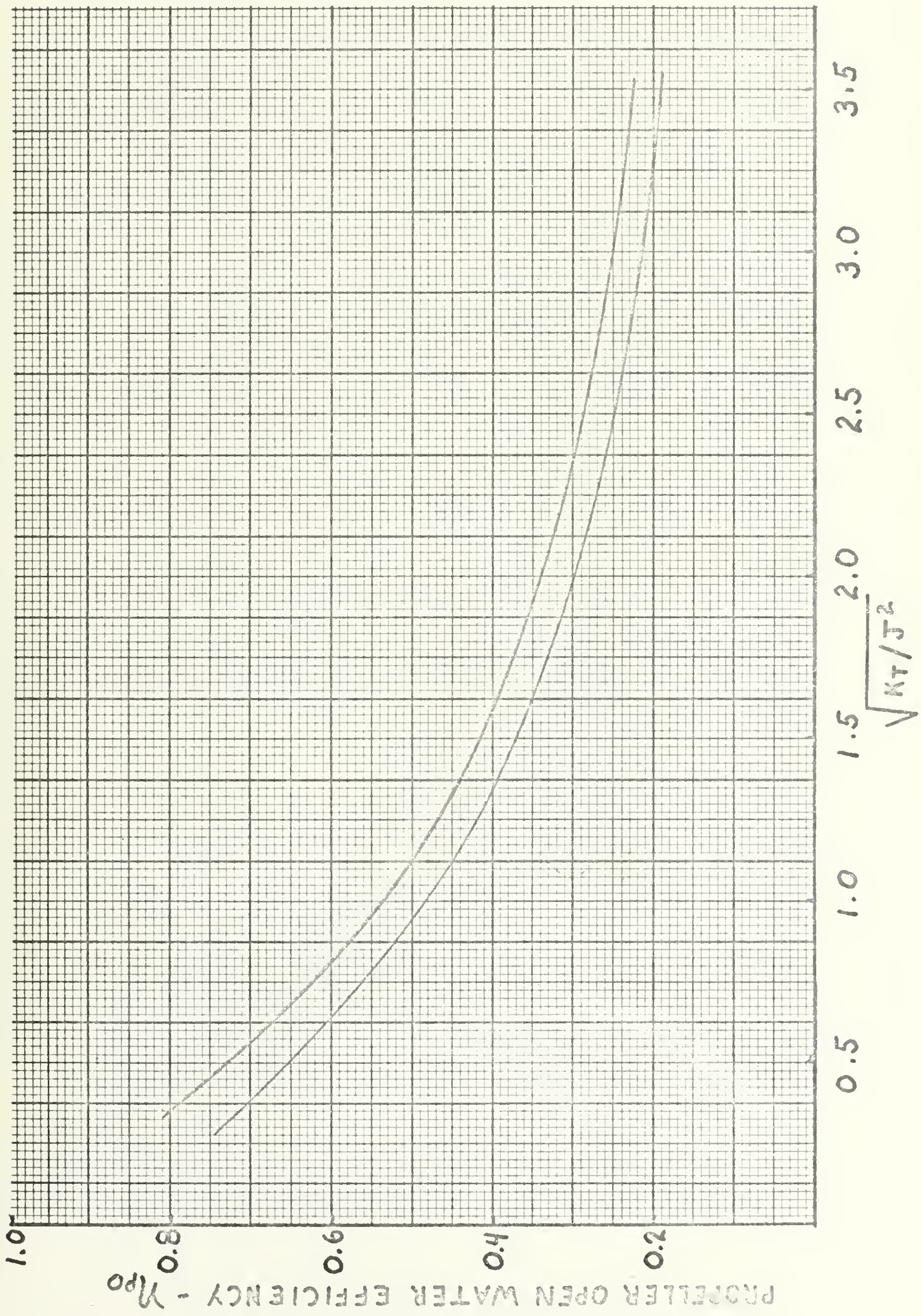
WAGENINGEN Four Bladed B-Screw Series:

Optimum Pitch-Diameter Ratio for Diameter Constraint



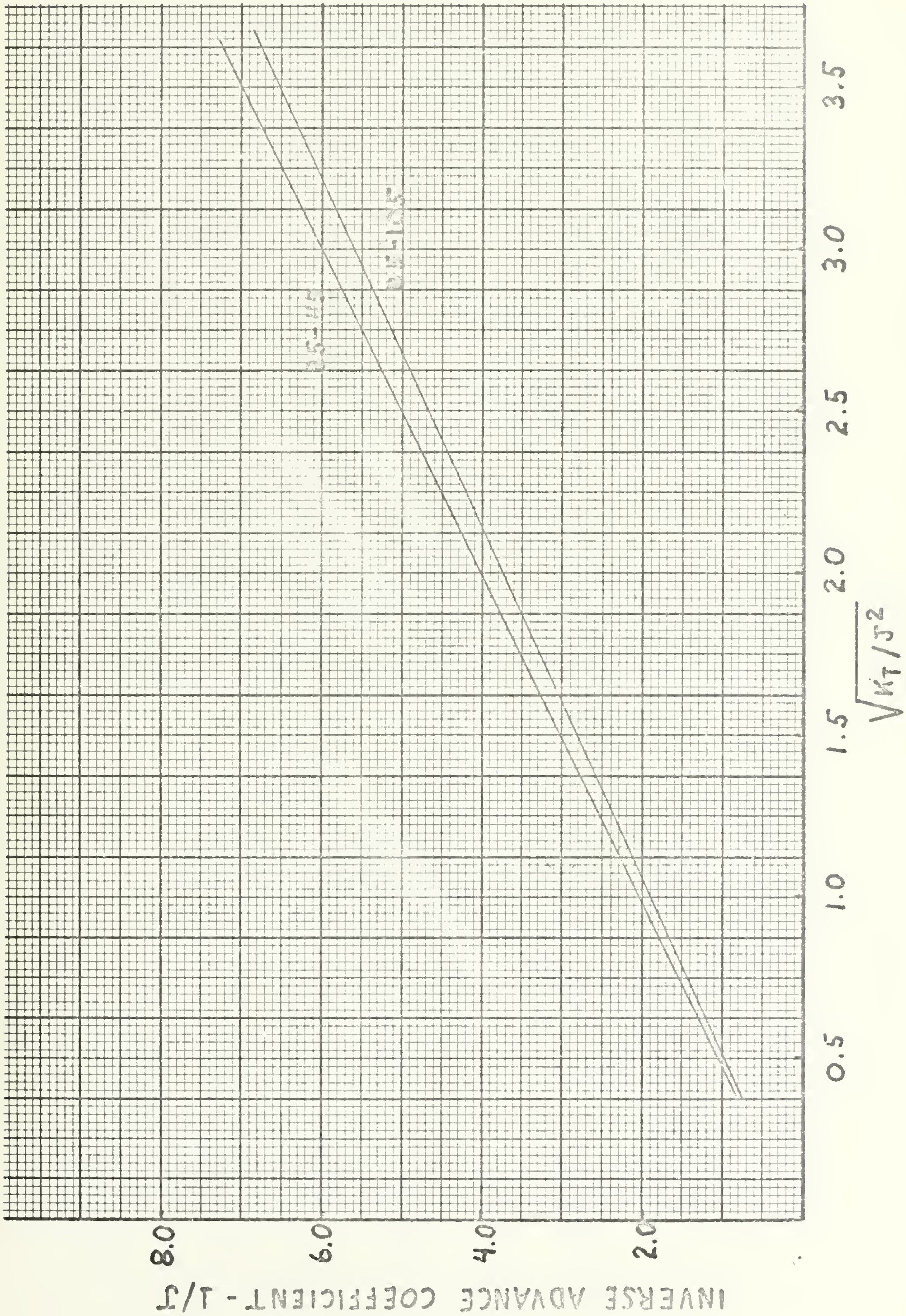
WAGENINGEN Five Bladed B-Screw Series:

Optimum Efficiency for Diameter Constraint



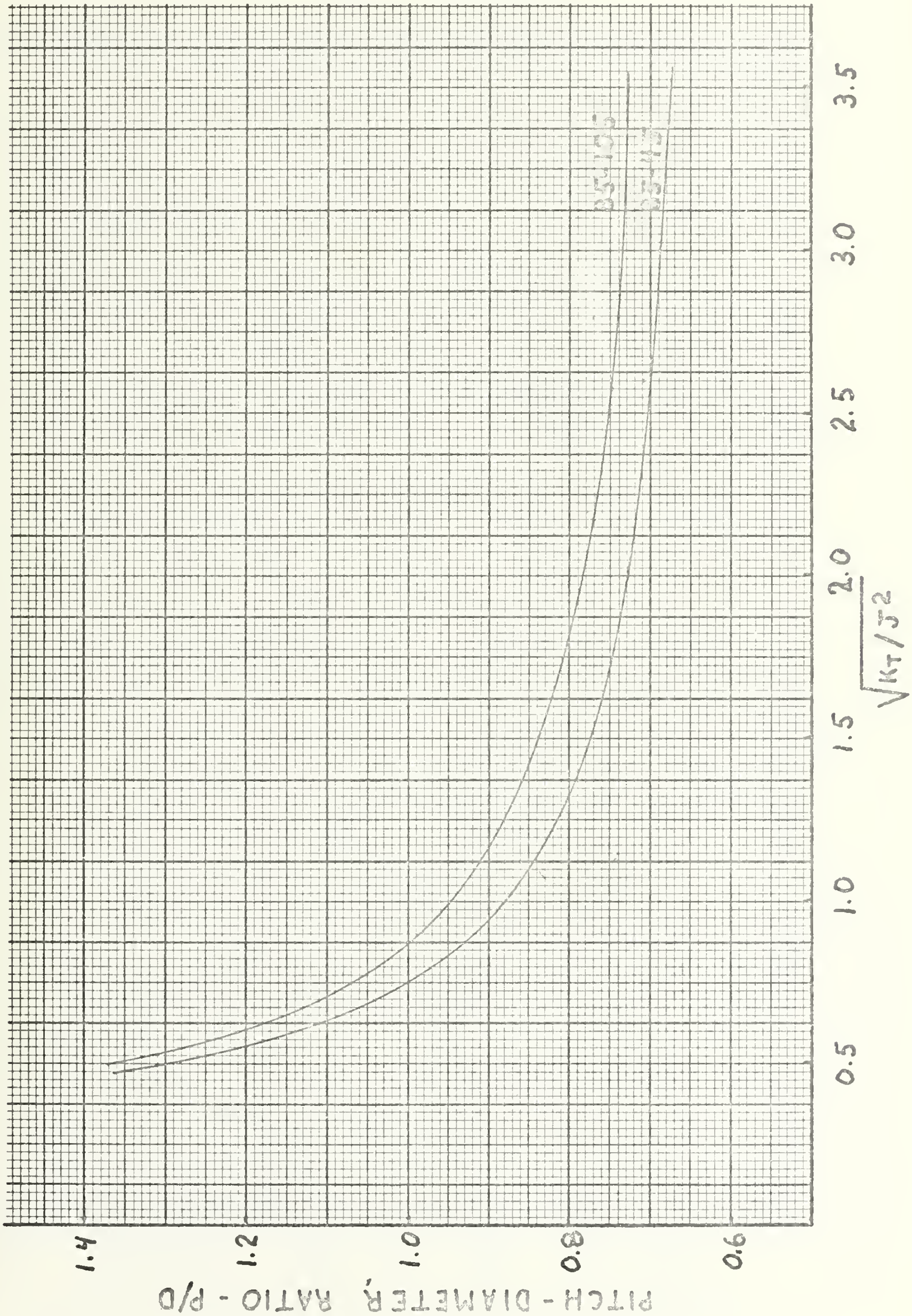
WAGENINGEN Five Bladed B-Screw Series:

Optimum Advance Ratio for Diameter Constraint



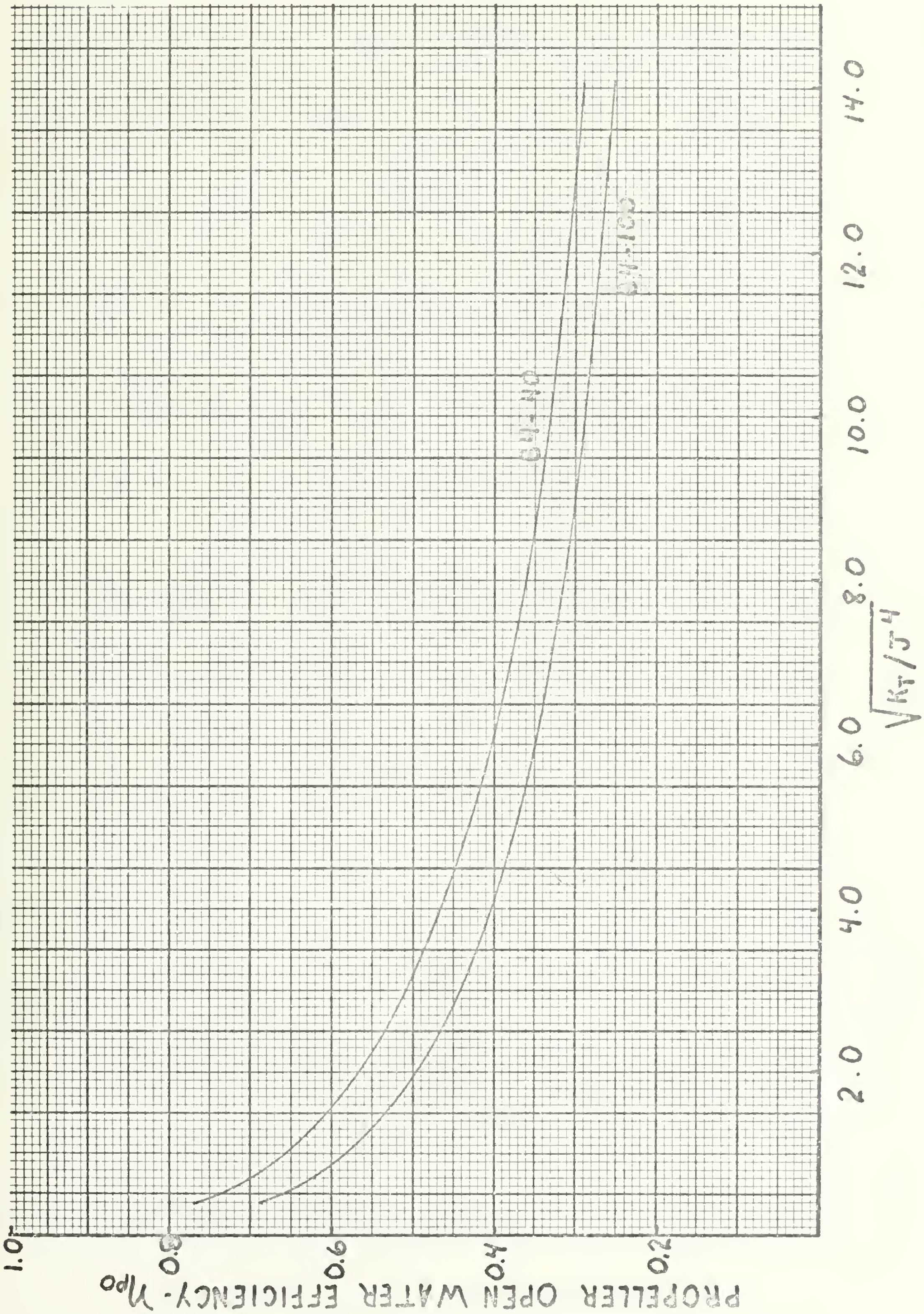
WAGENINGEN Five Bladed B-Screw Series:

Optimum Pitch-Diameter Ratio for Diameter Constraint



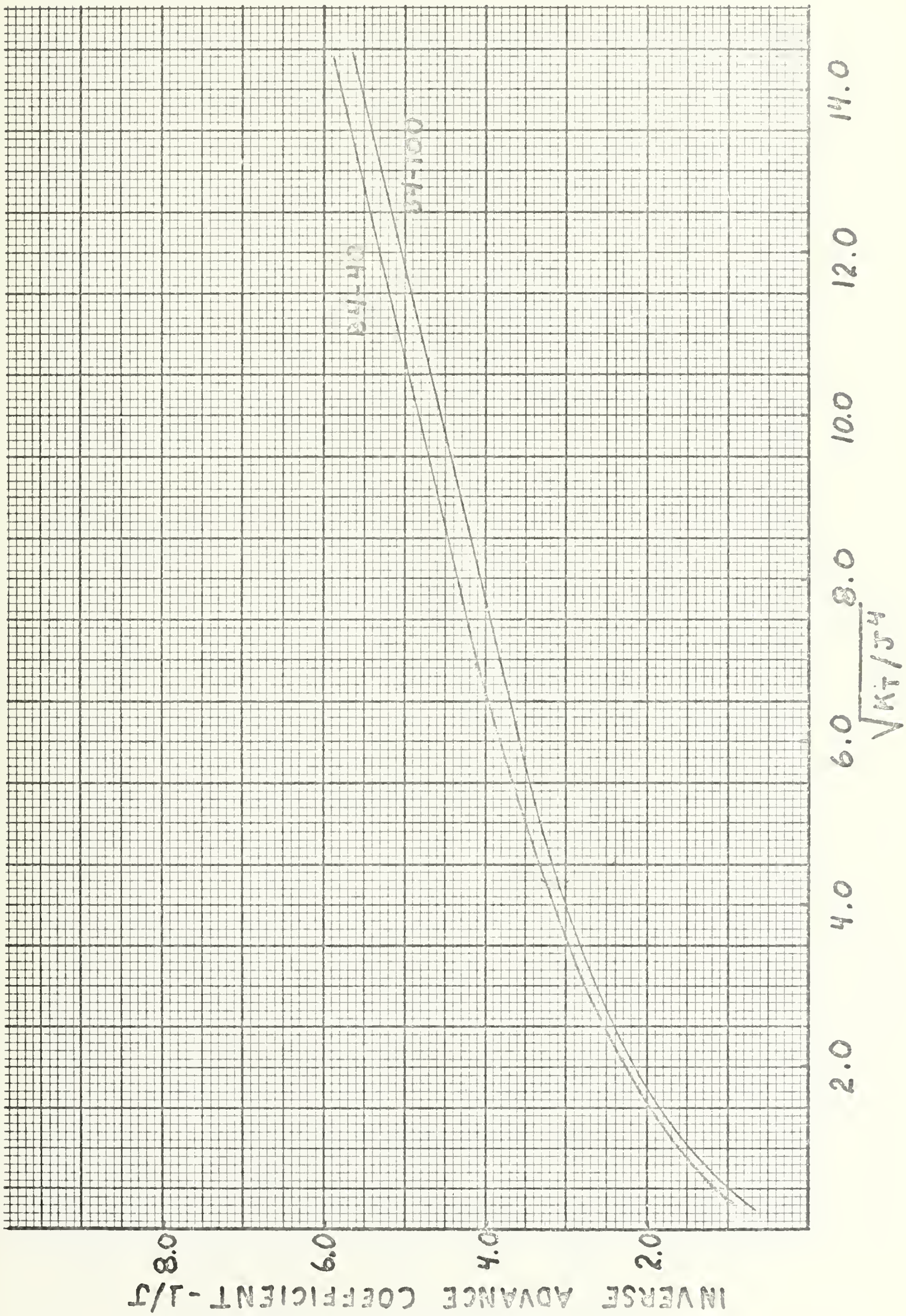
WAGENINGEN Four Bladed B-Screw Series:

Optimum Efficiency for RPM Constraint



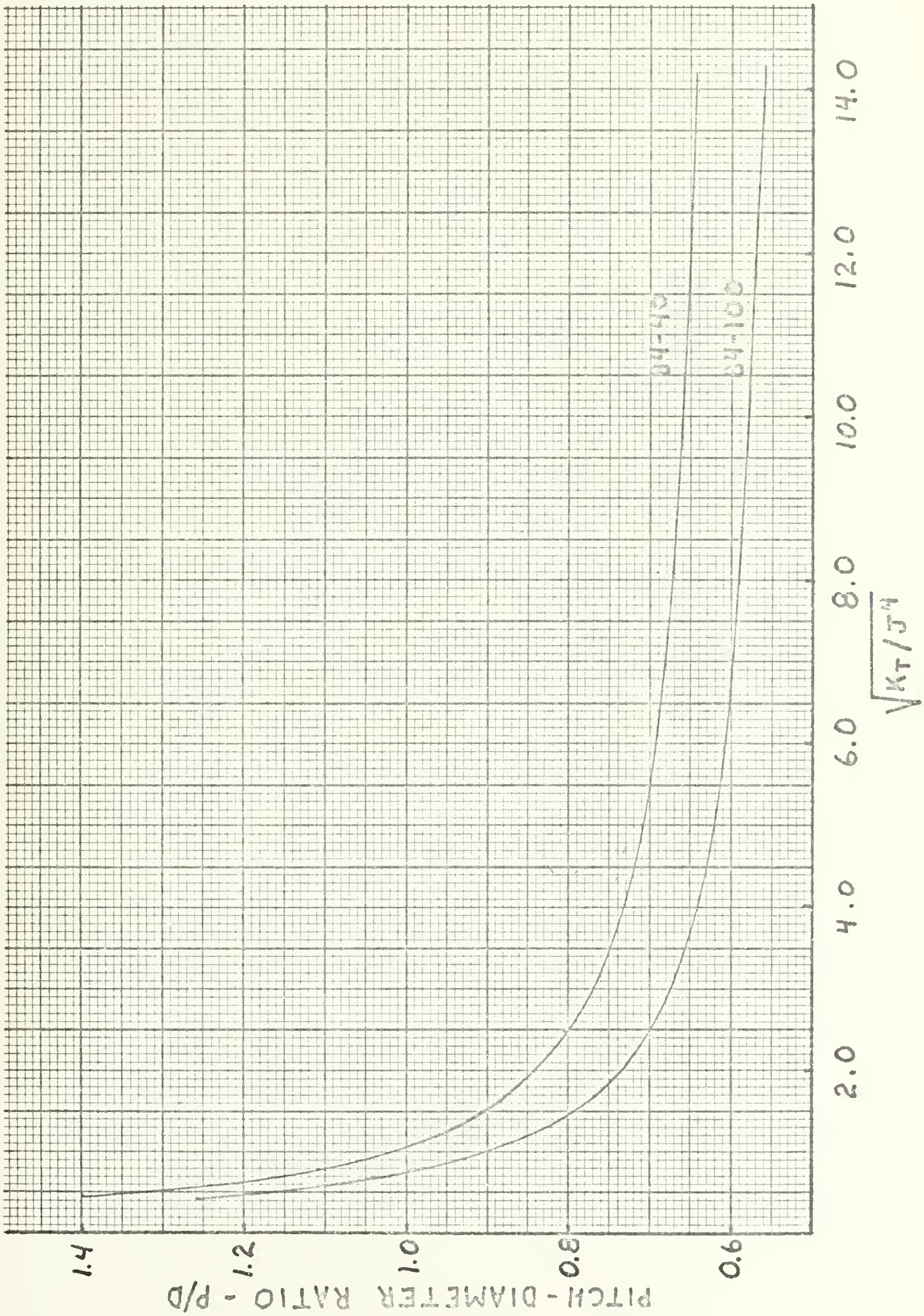
WAGENINGEN Four Bladed B-Screw Series:

Optimum Advance Ratio for RPM Constraint



WAGENINGEN Four Bladed B-Screw Series:

Optimum Pitch-Diameter Ratio for RPM Constraint



APPENDIX B.

PROPELLER CHARACTERISTIC

APPROXIMATION FORMULAS;

WAGENINGEN B4 AND B5 SERIES

1. B4-40 Wageningen B-Screw Series--Diameter Constraint

(a) η_{PO}

$.4 \le \sqrt{K_T/J^2} \le 2.0$

$\eta_{PO} = .1070313(K_T/J^2) - .52125\sqrt{K_T/J^2} + .956375$

$2.0 < \sqrt{K_T/J^2} \le 3.6$

$\eta_{PO} = .021094(K_T/J^2) - .20375\sqrt{K_T/J^2} + .665125$

(b) $1/J = 2.084615\sqrt{K_T/J^2} + .08$

(c) P/D

$.4 \le \sqrt{K_T/J^2} \le .44$

$P/D = 1.40$

$.44 < \sqrt{K_T/J^2} \le 1.0$

$P/D = 1.47788(K_T/J^2) - 3.11029\sqrt{K_T/J^2} + 2.48241$

$1.0 < \sqrt{K_T/J^2} \le 2.0$

$P/D = .126(K_T/J^2) - .531\sqrt{K_T/J^2} + 1.255$

$2.0 < \sqrt{K_T/J^2} \le 3.6$

$P/D = .0179688(K_T/J^2) - .13625\sqrt{K_T/J^2} + .897625$

2. B4-100 Wageningen B-Screw Series--Diameter Constraint

(a) η_{PO}

$.4 \le \sqrt{K_T/J^2} \le 2.0$

$\eta_{PO} = .1125(K_T/J^2) - .51875\sqrt{K_T/J^2} + .8945$

$2.0 < \sqrt{K_T/J^2} \le 3.6$

$\eta_{PO} = .0265625(K_T/J^2) - .22125\sqrt{K_T/J^2} + .64325$

(b) $1/J = 1.921053\sqrt{K_T/J^2}$

(c) P/D

$.4 \le \sqrt{K_T/J^2} \le .53$

$P/D = 1.40$

$.53 < \sqrt{K_T/J^2} \leq 1.0$

$P/D = 1.34545(K_T/J^2) - 2.958545\sqrt{K_T/J^2} + 2.590091$

$1.0 < \sqrt{K_T/J^2} \leq 2.0$

$P/D = .148(K_T/J^2) - .626\sqrt{K_T/J^2} + 1.455$

$2.0 < \sqrt{K_T/J^2} \leq 3.6$

$P/D = .0195313(K_T/J^2) - .15\sqrt{K_T/J^2} + 1.016875$

3. B5-45 Wageningen B-Screw Series--Diameter Constraint

(a) η_{PO}

$.4 \leq \sqrt{K_T/J^2} \leq 2.0$

$\eta_{PO} = .1210938(K_T/J^2) - .5625\sqrt{K_T/J^2} + .980625$

$2.0 < \sqrt{K_T/J^2} \leq 3.6$

$\eta_{PO} = .0203125(K_T/J^2) - .19125\sqrt{K_T/J^2} + .64125$

(b) $1/J = 1.986667\sqrt{K_T/J^2} + .04$

(c) P/D

$.4 \leq \sqrt{K_T/J^2} \leq .46$

$P/D = 1.4$

$.46 < \sqrt{K_T/J^2} \leq 1.0$

$P/D = 1.518609(K_T/J^2) - 3.183836\sqrt{K_T/J^2} + 2.543227$

$1.0 \leq \sqrt{K_T/J^2} \leq 2.0$

$P/D = .106(K_T/J^2) - .465\sqrt{K_T/J^2} + 1.237$

$2.0 < \sqrt{K_T/J^2} \leq 3.6$

$P/D = .0164063(K_T/J^2) - .13125\sqrt{K_T/J^2} + .927875$

4. B5-105 Wageningen B-Screw Series--Diameter Constraint

(a) η_{PO}

$.4 \leq \sqrt{K_T/J^2} \leq 2.0$

$$\eta_{PO} = .0921875(K_T/J^2) - .46625\sqrt{K_T/J^2} + .86275$$

$2.0 < \sqrt{K_T/J^2} \leq 3.6$

$$\eta_{PO} = .0234375(K_T/J^2) - .20\sqrt{K_T/J^2} + .60525$$

(b) $1/J = 1.846875\sqrt{K_T/J^2} + .04$

(c) P/D

$.4 \leq \sqrt{K_T/J^2} \leq .48$

$$P/D = 1.40$$

$.48 < \sqrt{K_T/J^2} \leq 1.0$

$$P/D = 1.233618(K_T/J^2) - 2.698832\sqrt{K_T/J^2} + 2.411214$$

$1.0 < \sqrt{K_T/J^2} \leq 2.0$

$$P/D = .124(K_T/J^2) - .532\sqrt{K_T/J^2} + 1.354$$

$2.0 < \sqrt{K_T/J^2} \leq 3.6$

$$P/D = .0164063(K_T/J^2) - .13125\sqrt{K_T/J^2} + .982875$$

5. B4-40 and B5-45 Wageningen B-Screw Series---RPM Constraint

(a) PO

$.4 \leq \sqrt{K_T/J^4} \leq 3.0$

$$\eta_{PO} = .0281065(K_T/J^4) - .1928698\sqrt{K_T/J^4} + .8326509$$

$3.0 < \sqrt{K_T/J^4} \leq 8.0$

$$\eta_{PO} = .00304(K_T/J^4) - .06264\sqrt{K_T/J^4} + .66756$$

$8.0 \leq \sqrt{K_T/J^4} \leq 14.0$

$$\eta_{PO} = .0008333(K_T/J^4) - .029826\sqrt{K_T/J^4} + .546296$$

(b) 1/J

$.4 \leq \sqrt{K_T/J^4} \leq 3.0$

$$1/J = - .127219(K_T/J^4) + 1.09793\sqrt{K_T/J^4} + .531183$$

$3.0 < \sqrt{K_T/J^4} \leq 8.5$

$1/J = -.0171901(K_T/J^4) + .528595\sqrt{K_T/J^4} + 1.248926$

$8.5 < \sqrt{K_T/J^4} \leq 14.0$

$1/J = .2272727\sqrt{K_T/J^4} + 2.568182$

(c) P/D

$.4 \leq \sqrt{K_T/J^4} \leq 1.0$

$P/D = 1.111111(K_T/J^4) - 2.355556\sqrt{K_T/J^4} + 2.264444$

$1.0 < \sqrt{K_T/J^4} \leq 2.0$

$P/D = .106(K_T/J^4) - .495\sqrt{K_T/J^4} + 1.409$

$2.0 < \sqrt{K_T/J^4} \leq 8.0$

$P/D = .0051667(K_T/J^4) - .0805\sqrt{K_T/J^4} + .9833333$

$8.0 < \sqrt{K_T/J^4} \leq 14.0$

$P/D = - .005\sqrt{K_T/J^4} + .71$

6. <u>B4-100 and B5-105 Wageningen B-Screw Series--RPM Constraint</u>

(a) η_{PO}

$.4 \leq \sqrt{K_T/J^4} \leq 3.0$

$\eta_{PO} = .0257396(K_T/J^4) - .1809763\sqrt{K_T/J^4} + .7482722$

$3.0 < \sqrt{K_T/J^4} \leq 8.0$

$\eta_{PO} = .00272(K_T/J^4) - .05432\sqrt{K_T/J^4} + .57548$

$8.0 < \sqrt{K_T/J^4} \leq 14.0$

$\eta_{PO} = .0005(K_T/J^4) - .0218333\sqrt{K_T/J^4} + .4576667$

(b) 1/J

$.4 \leq \sqrt{K_T/J^4} \leq 3.0$

$1/J = - .127219(K_T/J^4) + 1.09793\sqrt{K_T/J^4} + .531183$

$3.0 < \sqrt{K_T/J^4} \leq 8.5$

$$1/J = -\ .0171901(K_T/J^4) + .528595\sqrt{K_T/J^4} + 1.248926$$

$$8.5 < \sqrt{K_T/J^4} \leq 14.0$$

$$1/J = .2272727\sqrt{K_T/J^4} + 2.568182$$

(c) P/D

$$.4 \leq \sqrt{K_T/J^4} \leq 1.0$$

$$P/D = 1.111111(K_T/J^2) - 2.255556\sqrt{K_T/J^2} + 2.044444$$

$$1.0 < \sqrt{K_T/J^4} \leq 3.0$$

$$P/D = .051(K_T/J^4) - .318\sqrt{K_T/J^4} + 1.167$$

$$3.0 < \sqrt{K_T/J^4} \leq 6.0$$

$$P/D = .0037778(K_T/J^4) - .0563333\sqrt{K_T/J^4} + .8069999$$

$$6.0 < \sqrt{K_T/J^4} \leq 14.0$$

$$P/D = -\ .006875\sqrt{K_T/J^4} + .64625$$

APPENDIX C.

PROGRAM SOURCE LISTING

The Computer Program of this paper was written in FORTRAN IV, Level G-1, for use on the IBM Model 370/165 Digital Computer.

```
C      PROGRAM:  PRELIMINARY SHIP POWER PLANT EVALUATION AIDE
  200 READ(5,100)EHP,VKTS,THFAC,WKFAC,DENS,DIA,HGT,ETAR,ETASH,XINT,BKCCS
     1T,DCKLC,DCYLC,DMCST,DLCST,HOURS,RPMD,ETASHD,NBLAD,IYRS,KSTOP
  100 FORMAT(8F10.3/8F10.3/2F10.3,3I4)
      WRITE(6,101)EHP,DENS,THFAC,DCKLC,BKCCST,DIA,ETAR,WKFAC,DCYLC,XINT,
     1HGT,ETASH,RPMD,DLCST,HOURS,VKTS,ETASHD,NBLAD,DMCST,IYRS
  101 FORMAT('1',//////,45X,'INPUT',/,9X,'EHP   = ',F7.1,2X,'DEN     = ',F
     15.3,2X,'(1-T) =  ',F5.3,2X,'DCKLC = $',F5.2,2X,'BKCCST = $',F5.2,/
     2,9X,'DIA   = ',F7.1,2X,'ETAR    = ',F5.3,2X,'(1-W) =  ',F5.3,2X,'DCY
     3LC = $',F5.2,2X,'INTER  = ',F6.2,/,9X,'HGT   = ',F7.1,2X,'ETASH  =
     4',F5.3,2X,'RPMD   =  ',F5.1,2X,'DLCST = $',F5.2,2X,'HOURS  = ',F6.0
     5,/,9X,'VKTS = ',F7.1,2X,'ETASHD = ',F5.3,2X,'NBLAD =    ',I4,2X,'DM
     6CST = $',F5.2,2X,'YEARS  =    ',I4)
C      CALCULATE PROPELLER CHARACTERISTICS BASED ON WAGENINGEN B4 AND B5
C      SERIES
      N=1
      I=0
      J=1
C      DETERMINE REQUIRED BLADE AREA RATIO FOR 5 PERCENT BACK CAVITATION
C      APPROXIMATION AND THE DIAMETER CONSTRAINT
      XKTJ2=EHP*550./((VKTS*1.6915)**3*DENS*DIA**2*THFAC*WKFAC**2)
      DC=SQRT(XKTJ2)
      IF(DC.LT..4.OR.DC.GT.3.6)GO TO 34
      IF(NBLAD.EQ.5)GO TO 5
      IF(NBLAD.NE.4)GO TO 35
      IF(DC.GE..4.AND.DC.LE..44)GO TO 1
      IF(DC.GT..44.AND.DC.LE.1.0)GO TO 2
      IF(DC.GT.1.0.AND.DC.LE.2.0)GO TO 3
      PD1=.0179688*DC**2-.13625*DC+.897625
      GO TO 4
    1 PD1=1.4
      GO TO 4
    2 PD1=1.47788*DC**2-3.11029*DC+2.48241
      GO TO 4
    3 PD1=.126*DC**2-.531*DC+1.255
    4 XJINV1=2.084615*DC+.08
```

```
      GO TO 10
    5 IF(DC.GE..4.AND.DC.LE..46)GO TO 6
      IF(DC.GT..46.AND.DC.LE.1.0)GO TO 7
      IF(DC.GT.1.0.AND.DC.LE.2.0)GO TO 8
      PD1=.0164063*DC**2-.13125*DC+.927875
      GO TO 9
    6 PD1=1.4
      GO TO 9
    7 PD1=1.518609*DC**2-3.183836*DC+2.543227
      GO TO 9
    8 PD1=.106*DC**2-.465*DC+1.237
    9 XJINV1=1.986667*DC+.04
      ADVC=1./XJINV1
   10 REVSEC=VKTS*1.6915*WKFAC*XJINV1/DIA
      POPV=14.45+.45*HGT
      QT=(VKTS*WKFAC/7.12)**2+(REVSEC*60.*DIA/329.)**2
      CAVNUM=POPV/QT
      TAUC1=.2652556*CAVNUM**.607362
      THRST=EHP*550./(THFAC*VKTS*1.6915)
      AP=THRST/(QT*TAUC1)
      AD=AP/(1.067-.229*PD1)
      FAF=AD/(3.141593*DIA**2*36.)
C     TEST FOR SATISFACTORY FA/F
C     INTERPOLATE FOR UPDATED CHARACTERISTICS BASED ON FA/F REQUIRED
      IF(NBLAD.EQ.5)GO TO 16
      IF(FAF.LE..4)GO TO 26
      IF(FAF.GT.1.0)GO TO 36
      IF(DC.GE..4.AND.DC.LE..53)GO TO 11
      IF(DC.GT..53.AND.DC.LE.1.0)GO TO 12
      IF(DC.GT.1.0.AND.DC.LE.2.0)GO TO 13
      PD2=.0195313*DC**2-.15*DC+1.016875
      GO TO 14
   11 PD2=1.4
      GO TO 14
   12 PD2=1.34545*DC**2-2.958545*DC+2.590091
      GO TO 14
```

```
13 PD2=.148*DC**2-.626*DC+1.455
14 XJINV2=1.921053*DC
15 PD3=((FAF-.4)/.6)*(PD2-PD1)+PD1
   XJINV3=XJINV1-((FAF-.4)/.6)*(XJINV1-XJINV2)
   GO TO 22
16 IF(FAF.LE..45)GO TO 29
   IF(FAF.GT.1.05)GO TO 36
   IF(DC.GE..4.AND.DC.LE..48)GO TO 17
   IF(DC.GT..48.AND.DC.LE.1.0)GO TO 18
   IF(DC.GT.1.0.AND.DC.LE.2.0)GO TO 19
   PD2=.0164063*DC**2-.13125*DC+.982875
   GO TO 20
17 PD2=1.4
   GO TO 20
18 PD2=1.233618*DC**2-2.698832*DC+2.411214
   GO TO 20
19 PD2=.124*DC**2-.532*DC+1.354
20 XJINV2=1.846875*DC+.04
21 PD3=((FAF-.45)/.6)*(PD2-PD1)+PD1
   XJINV3=XJINV1-((FAF-.45)/.6)*(XJINV1-XJINV2)
22 REVSC1=VKTS*1.6915*WKFAC*XJINV3/DIA
   QT1=(VKTS*WKFAC/7.12)**2+(REVSC1*60.*DIA/329.)**2
   CAVNM1=POPV/QT1
   TAUC2=.2917812*CAVNM1**.607362
   TAUC2L=.2387300*CAVNM1**.607362
   AP1=(1.067-.229*PD3)*FAF*3.141593*DIA**2*36.
   TAUC3=THRST/(AP1*QT1)
C     TEST FOR SATISFIED CAVITATION CRITERION
   IF(TAUC3.LE.TAUC2.AND.TAUC3.GE.TAUC2L)GO TO 24
C     ITERATE FOR UPDATED FA/F REQUIRED AND PROPELLER CHARACTERISTICS
   I=I+J
   IF(I.GE.5)GO TO 37
   TAUC1=.2652556*CAVNM1**.607362
   AP2=THRST/(QT1*TAUC1)
   AD1=AP2/(1.067-.229*PD3)
   FAF=AD1/(3.141593*DIA**2*36.)
```

```
      IF(NBLAD.EQ.5)GO TO 23
      IF(FAF.LE.1.0)GO TO 15
      GO TO 36
   23 IF(FAF.LE.1.05)GO TO 21
      GO TO 36
   24 N=2
      PD1=PD3
      XJINV1=XJINV3
      ADVC=1./XJINV1
      TAUC1=TAUC3
      REVSEC=REVSC1
      CAVNUM=CAVNM1
C     DETERMINE PROPELLER OPEN WATER EFFICIENCY
   25 IF(NBLAD.EQ.5)GO TO 29
   26 IF(DC.GE..4.AND.DC.LE.2.0)GO TO 28
      ETAPO1=.0210938*DC**2-.20375*DC+.665125
      IF(N.EQ.1)GO TO 32
      ETAPO2=.0265625*DC**2-.22125*DC+.64325
   27 ETAPO=ETAPO1-((FAF-.4)/.6)*(ETAPO1-ETAPO2)
      GO TO 33
   28 ETAPO1=.1070313*DC**2-.52125*DC+.956375
      IF(N.EQ.1)GO TO 32
      ETAPO2=.1125*DC**2-.51875*DC+.8945
      GO TO 27
   29 IF(DC.GE..4.AND.DC.LE.2.0)GO TO 31
      ETAPO1=.0203125*DC**2-.19125*DC+.64125
      IF(N.EQ.1)GO TO 32
      ETAPO2=.0234375*DC**2-.2*DC+.60525
   30 ETAPO=ETAPO1-((FAF-.45)/.6)*(ETAPO1-ETAPO2)
      GO TO 33
   31 ETAPO1=.1210938*DC**2-.5625*DC+.980625
      IF(N.EQ.1)GO TO 32
      ETAPO2=.0921875*DC**2-.46625*DC+.86275
      GO TO 30
   32 ETAPO=ETAPO1
C     DETERMINE PROPULSION COEFFICIENT
```

```
   33 PC=THFAC/WKFAC*ETAPC*ETAR*ETASH
      RPM=REVSEC*60.
      WRITE(6,102)ETAPC,ADVC,RPM,CAVNUM,PC1,FAF,DC,TAUC1
      GC TO 38
   34 WRITE(6,103)DC
      GC TO 998
   35 WRITE(6,104)
      GC TO 998
   36 WRITE(6,105)FAF
      GO TO 998
   37 WRITE(6,106)TAUC3,TAUC2,TAUC2L
      GO TO 998
  102 FCRMAT('0',38X,'PRCPELLER PARAMETERS',/,9X,'EFFIC. = ',F7.5,1X,'AD
     1V.COEF. = ',F4.2,4X,'RPM          = ',F5.1,4X,'CAV.NUM. = ',F4.2,/,
     29X,'P/D     = ',F4.2,4X,'FAF         = ',F4.2,4X,'DIA.CCNSTR. = ',F5.
     33,4X,'TAUC      = ',F4.2)
  103 FCRMAT('0',9X,'DIAMETER CCNSTRAINT CUTSIDE LIMITS',3X,'DC = ',F8.6
     1)
  104 FORMAT('0',9X,'NBLAD NCT ACCEPTABLE')
  105 FORMAT('0',9X,'FA/F OUTSIDE LIMITS',3X,'FA/F = ',F8.5)
  106 FORMAT('0',9X,'CAVITATICN INDEX WILL NCT CCNVERGE IN 5 ITERARICNS'
     1,/,' ',9X,'TAUC3 = ',F8.6,3X,'TAUC2 = ',F8.6,3X,'TAUC2L = '.F8.6)
C     DETERMINE PRESENT VALUE FACTCR
   38 XINTFC=(1+XINT)**IYRS
      XPVFAC=(XINTFC-1.)/(XINTFC*XINT)
      RPM1=1.1*RPM
C     TEST RPM TO DETERMINE IF SLCW DIESEL CALCULATICN (RPM CCNSTRAINT)
C     IS REQUIRED
      IF(RPMD.GE.RPM1)GC TC 50
      RPMDL=RPMD-10.
      RPMDU=RPMD+10.
      IF(RPM.GE.RPMDL.AND.RPM.LE.RPMDU)GC TC 300
   39 DLOIC=0.
      DLCMC=0.
      DLCFC=0.
      DLOLC=0.
```

```
      DLMNGC=0.
      DLAC=0.
      DLPVAC=0.
      DLPVT=0.
      DLWGT=0.
      DLAVAL=0.
      SHPD=0.0
      PCD=0.0
      GO TO 400
C     DETERMINE PROPELLER CHARACTERISTICS USING RPM CONSTRAINT (SAME
C     PROCEDURE AS DIAMETER CONSTRAINT)
   50 K=0
      L=1
      M=1
      REVD=RPMD/60.
      XKTJ4=EHP*550.*REVD**2/((VKTS*1.6915)**5*DENS*THFAC*WKFAC**4)
      RC=SQRT(XKTJ4)
      IF(RC.LT..4.OR.RC.GT.14.0)GO TO 83
      IF(RC.GE..4.AND.RC.LE.1.0)GO TO 51
      IF(RC.GT.1.0.AND.RC.LE.2.0)GO TO 52
      IF(RC.GT.2.0.AND.RC.LE.8.0)GO TO 53
      PDD1=-.005*RC+.71
      GO TO 54
   51 PDD1=1.111111*RC**2-2.355556*RC+2.264444
      GO TO 54
   52 PDD1=.106*RC**2-.495*RC+1.409
      GO TO 54
   53 PDD1=.0051667*RC**2-.0835*RC+.9833333
   54 IF(RC.GE..4.AND.RC.LE.3.0)GO TO 55
      IF(RC.GT.3.0.AND.RC.LE.8.5)GO TO 56
      DJINV1=.2272727*RC+2.568182
      GO TO 57
   55 DJINV1=-.127219*RC**2+1.09793*RC+.531183
      GO TO 57
   56 DJINV1=-.0171901*RC**2+.528595*RC+1.2489256
   57 DADVC=1./DJINV1
```

```
      DIAD=VKTS*1.6915*WKFAC*DJINV1/REVD
      IF(DIAD.LE.DIA)GO TO 157
      DIAD=DIA
  157 DQT=(VKTS*WKFAC/7.12)**2+(RPMD*DIAD/329.)**2
      CAVNMD=POPV/DQT
      TAUC1D=.2652556*CAVNMD**.607362
      AP=THRST/(DQT*TAUC1D)
      AD=AP/(1.067-.229*PDD1)
      FAFD=AD/(3.141593*DIAD**2*36.)
      IF(NBLAD.EQ.5)GO TO 58
      IF(FAFD.LE..4)GO TO 72
      IF(FAFD.GT.1.0)GO TO 84
      GO TO 59
   58 IF(FAFD.LE..45)GO TO 72
      IF(FAFD.GT.1.05)GO TO 84
   59 IF(RC.GE..4.AND.RC.LE.1.0)GO TO 60
      IF(RC.GT.1.0.AND.RC.LE.3.0)GO TO 61
      IF(RC.GT.3.0.AND.RC.LE.6.0)GO TO 62
      PDD2=-.006875*RC+.64625
      GO TO 63
   60 PDD2=1.111111*RC**2-2.255556*RC+2.044444
      GO TO 63
   61 PDD2=.051*RC**2-.318*RC+1.167
      GO TO 63
   62 PDD2=.0037778*RC**2-.0563333*RC+.8069999
   63 IF(RC.GE..4.AND.RC.LE.3.0)GO TO 64
      IF(RC.GT.3.0.AND.RC.LE.8.0)GO TO 65
      DJINV2=.2316667*RC+2.276667
      GO TO 66
   64 DJINV2=-.1153846*RC**2+1.034615*RC+.5046154
      GO TO 66
   65 DJINV2=-.016*RC**2+.488*RC+1.25
   66 IF(NBLAD.EQ.5)GO TO 68
   67 PDD3=PDD1-((FAFD-.4)/.6)*(PDD1-PDD2)
      DJINV3=DJINV1-((FAFD-.4)/.6)*(DJINV1-DJINV2)
      GO TO 69
```

```
 68 PDD3=PDD1-((FAFD-.45)/.6)*(PDD1-PDD2)
    DJINV3=DJINV1-((FAFD-.45)/.6)*(DJINV1-DJINV2)
 69 DIAD1=VKTS*1.6915*WKFAC*DJINV3/REVD
    IF(DIAD1.LE.DIA)GO TO 169
    DIAD1=DIA
169 DQT1=(VKTS*WKFAC/7.12)**2+(RPMD*DIAD1/329.)**2
    CAVND1=POPV/DQT1
    TAUC2D=.2917812*CAVND1**.607362
    TAC2DL=.2387300*CAVND1**.607362
    AP1=(1.067-.229*PDD3)*FAFD*3.141593*DIAD1**2*36.
    TAUC3D=THRST/(AP1*DQT1)
    IF(TAUC3D.LE.TAUC2D.AND.TAUC3D.GE.TAC2DL)GO TO 71
    K=K+L
    IF(K.GE.5)GO TO 85
    TAUC1D=.2652556*CAVND1**.607362
    AP2=THRST/(DQT1*TAUC1D)
    AD1=AP2/(1.067-.229*PDD3)
    FAFD=AD1/(3.141593*DIAD1**2*36.)
    IF(NBLAD.EQ.5)GO TO 70
    IF(FAFD.LE.1.0)GO TO 67
    GO TO 84
 70 IF(FAFD.LE.1.05)GO TO 68
    GO TO 84
 71 M=2
    PDD1=PDD3
    DJINV1=DJINV3
    DADVC=1./DJINV1
    DIAD=DIAD1
    TAUC1D=TAUC3D
    CAVNMD=CAVND1
 72 IF(RC.GE..4.AND.RC.LE.3.0)GO TO 73
    IF(RC.GT.3.0.AND.RC.LE.8.0)GO TO 74
    ETAPD1=.0008333*RC**2-.029826*RC+.546296
    GO TO 75
 73 ETAPD1=.0281065*RC**2-.1928698*RC+.8326509
    GO TO 75
```

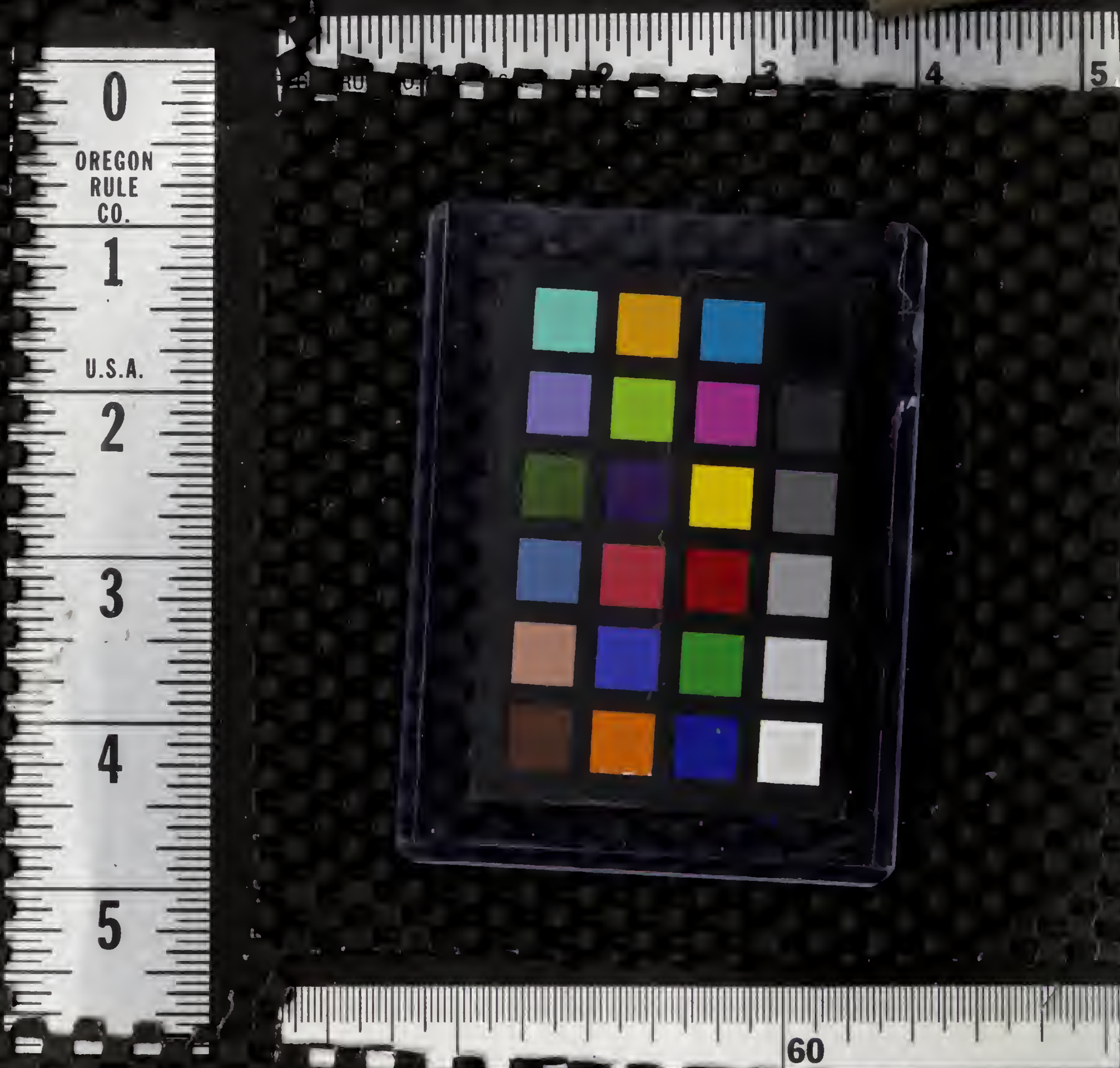
```
 74 ETAPD1=.00304*RC**2-.06264*RC+.66756
 75 IF(M.EQ.1)GO TO 80
    IF(RC.GE..4.AND.RC.LE.3.0)GO TO 76
    IF(RC.GT.3.0.AND.RC.LE.8.0)GO TO 77
    ETAPD2=.0005*RC**2-.0218333*RC+.4576667
    GO TO 78
 76 ETAPD2=.0257396*RC**2-.1809763*RC+.7482722
    GO TO 78
 77 ETAPD2=.00272*RC**2-.05432*RC+.57548
 78 IF(NBLAD.EQ.5)GO TO 79
    ETAPOD=ETAPD1-((FAFD-.4)/.6)*(ETAPD1-ETAPD2)
    GO TO 81
 79 ETAPOD=ETAPD1-((FAFD-.45)/.6)*(ETAPD1-ETAPD2)
    GO TO 81
 80 ETAPOD=ETAPD1
 81 IF(ETAPO.GT.ETAPOD)GO TO 82
    ETAPOD=ETAPO
 82 PCD=THFAC/WKFAC*ETAPOD*ETAR*ETASHD
    WRITE(6,107)ETAPOD,DADVD,DIAD,CAVNMD,PDD1,FAFD,RC,TAUC1D
    GO TO 301
 83 WRITE(6,108)RC
    GO TO 39
 84 WRITE(6,109)FAFD
    GO TO 39
 85 WRITE(6,110)TAUC3D,TAUC2D,TAC2DL
    GO TO 39
107 FORMAT(' ',35X,'SLOW SPEED DIESEL PROPELLER',/,9X,'EFFIC. = ',F7.5
   1,1X,'ADV.COEF. = ',F4.2,4X,'DIAMETER    = ',F5.2,4X,'CAV.NUM. = ',
   2F4.2,/,9X,'P/D     = ',F4.2,4X,'FA/F       = ',F4.2,4X,'RPM CONSTR.
   3= ',F5.2,4X,'TAUC      = ',F4.2)
108 FORMAT(' ',35X,'SLOW SPEED DIESEL PROPELLER',/,9X,'RPM CONSTRAINT
   1OUTSIDE LIMITS',3X,'RC = ',F8.6)
109 FORMAT(' ',35X,'SLOW SPEED DIESEL PROPELLER',/,9X,'FA/F OUTSIDE LI
   1MITS',3X,'FA/F = ',F8.5)
110 FORMAT(' ',35X,'SLOW SPEED DIESEL PROPELLER',/,9X,'CAVITATION INDE
   1X WILL NOT CONVERGE IN 5 ITERATIONS',/,9X,'TAUC3D = ',F8.6,3X,'TAU
```

```
     2C2D = ',F8.6,3X,'TAC2DL = ',F8.6)
  300 PCD=PC
C     DETERMINE SLOW DIESEL PLANT POWER RATING
  301 SHPD=EHP/PCD
C     DETERMINE SLOW DIESEL PLANT COSTS
      DLOIC=477800.*(SHPD/1000.)**.63
      DLOMC=4.2*SHPD
      SFCLOD=.433*(SHPD/1000.)**(-.055)
      DLOFC=(BKCCST*7.48*38.*SFCLOD*HOURS*SHPD)/(42.*2240.)
      DLOLC=(DCKLC*.043+DCYLC*.111)*(SHPD/1000.)*HOURS
      IF(SHPD.GT.30000.)GO TO 302
      DLMNGC=180100.
      GO TO 303
  302 DLMNGC=222000.
  303 DLAC=DLOMC+DLOFC+DLOLC+DLMNGC
      DLPVAC=DLAC*XPVFAC
      DLPVT=DLOIC+DLPVAC
      DLWGT=.05*SHPD+500.
      DLAVAL=.939
C     DETERMINE GEARED PLANT POWER RATING
  400 SHP=EHP/PC
C     DETERMINE IMPROVED SECOND GENERATION GAS TURBINE PLANT COSTS
      GTLIC=601700.*(SHP/1000.)**.629
      GTLMC=3.47*SHP
      IF(SHP.LE.19200.)GO TO 401
      IF(SHP.GT.19200..AND.SHP.LE.38400.)GO TO 402
      SFCGTL=.885*(SHP/3000.)**(-.254)
      GO TO 403
  401 SFCGTL=.885*(SHP/1000.)**(-.254)
      GO TO 403
  402 SFCGTL=.885*(SHP/2000.)**(-.254)
  403 GTLFC=(DMCST*7.48*42.3*SFCGTL*HOURS*SHP)/(42.*2240.)
      GTLLC=0.
      GTLMGC=122000.
      GTLAC=GTLMC+GTLFC+GTLMGC
      GTLPVA=GTLAC*XPVFAC
```

```
      GTLPVT=GTLIC+GTLPVA
      GTLWGT=.015*SHP+220.
      GTLAVL=.983
C     DETERMINE FIRST AND SECOND GENERATION GAS TURBINE PLANT COSTS
      GTFIC=861000.*(SHP/1000.)**.442
      GTFMC=3.47*SHP
      IF(SHP.LE.20000.)GO TO 404
      IF(SHP.LE.34400..AND.SHP.GT.20000.)GO TO 405
      IF(SHP.LE.40000..AND.SHP.GT.34400.)GO TO 406
      SFCGTF=.846*(SHP/2000.)**(-.171)
      GO TO 407
  404 SFCGTF=1.335*(SHP/1000.)**(-.324)
      GO TO 407
  405 SFCGTF=.846*(SHP/1000.)**(-.171)
      GO TO 407
  406 SFCGTF=1.335*(SHP/2000.)**(-.324)
  407 GTFFC=(DMCST*7.48*42.3*SFCGTF*HOURS*SHP)/(42.*2240.)
      GTFLC=0.
      GTFMGC=122000.
      GTFAC=GTFMC+GTFFC+GTFMGC
      GTFPVA=GTFAC*XPVFAC
      GTFPVT=GTFIC+GTFPVA
      GTFWGT=GTLWGT
      GTFAVL=.983
C     DETERMINE MEDIUM SPEED DIESEL PLANT COSTS
  500 IF(SHP.LE.18000.)GO TO 501
      IF(SHP.GT.18000..AND.SHP.LE.36000.)GO TO 502
      SFCDM=.455*(SHP/3000.)**(-.057)
      GO TO 503
  501 SFCDM=.455*(SHP/1000.)**(-.057)
      GO TO 503
  502 SFCDM=.455*(SHP/2000.)**(-.057)
  503 DMIC=173600.*(SHP/1000.)**.8614
      DMMC=4.2*SHP
      DMFC=(BKCCST*7.48*38.*SFCDM*HOURS*SHP)/(42.*2240.)
      DMLC=DLCST*.33*(SHP/1000.)*HOURS
```

```
      IF(SHP.GT.30000.)GO TO 504
      DMMNGC=180100.
      GO TO 505
  504 DMMNGC=202200.
  505 DMAC=DMMC+DMFC+DMLC+DMMNGC
      DMPVAC=DMAC*XPVFAC
      DMPVT=DMIC+DMPVAC
      DMWGT=.04*SHP+150.
      DMAVAL=.925
C     DETERMINE NON-REHEAT STEAM PLANT COSTS
  600 STNRIC=550200.*(SHP/1000.)**.6
      STNRMC=24560.+.98*SHP
      IF(SHP.GT.20000.)GO TO 601
      SFCSNR=.861*(SHP/1000.)**(-.211)
      GO TO 602
  601 SFCSNR=.572*(SHP/1000.)**(-.074)
  602 STNRFC=(BKCCST*7.48*38.*SFCSNR*HOURS*SHP)/(42.*2240.)
      STNRLC=0.
      SNRMGC=190600.
      STNRAC=STNRMC+STNRFC+SNRMGC
      SNRPVA=STNRAC*XPVFAC
      SNRPVT=STNRIC+SNRPVA
      STNRWT=.0215*SHP+440.
      STNRAL=.958
C     DETERMINE REHEAT STEAM PLANT COSTS
      STRHIC=1.07*STNRIC
      STRHMC=1.07*STNRMC
      SFCSRH=.493*(SHP/1000.)**(-.059)
      STRHFC=(BKCCST*7.48*38.*SFCSRH*HOURS*SHP)/(42.*2240.)
      STRHLC=0.
      SRHMGC=190600.
      STRHAC=STRHMC+STRHFC+SRHMGC
      SRHPVA=STRHAC*XPVFAC
      SRHPVT=STRHIC+SRHPVA
      STRHWT=STNRWT
      STRHAL=.958
```

```
      WRITE(6,111)SHP,PC,SHPD,PCD
  111 FORMAT('0',22X,'PLANT/SHAFT',25X,'SLOW DIESEL PLANT/SHAFT',/,9X,'S
     1HP = ',F7.1,6X,'PROP.COEF. = ',F4.2,4X,'SHP = ',F7.1,6X,'PROP.COEF
     2. = ',F4.2)
      WRITE(6,112)STRHIC,STNRIC,DLCIC,DMIC,GTFIC,GTLIC,STRHMC,STNRMC,DLO
     1MC,DMMC,GTFMC,GTLMC,STRHFC,STNRFC,DLOFC,DMFC,GTFFC,GTLFC,STRHLC,ST
     2NRLC,DLOLC,DMLC,GTFLC,GTLLC,SRHMGC,SNRMGC,DLMNGC,DMMNGC,GTFMGC,GTL
     3MGC,STRHAC,STNRAC,DLAC,DMAC,GTFAC,GTLAC,SRHPVA,SNRPVA,DLPVAC,DMPVA
     4C,GTFPVA,GTLPVA,SRHPVT,SNRPVT,DLPVT,DMPVT,GTFPVT,GTLPVT,STRHWT,STN
     5RWT,DLWGT,DMWGT,GTFWGT,GTLWGT,STRHAL,STNRAL,DLAVAL,DMAVAL,GTFAVL,G
     6TLAVL
  112 FORMAT('0',44X,'ECONOMIC PARAMETERS',/,32X,'STEAM',21X,'DIESEL',17
     1X,'GAS TURBINE',/,40X,'NON-         SLOW          MEDIUM         A/C
     2        IMP. A/C',/,26X,'REHEAT        REHEAT       SPEED          SPE
     3ED          DERIV.          DERIV.',//,9X,'INVESTMENT      $',F10.0,'  $
     4',F10.0,'  $',F10.0,'  $',F10.0,'  $',F10.0,'  $',F10.0,/,9X,'ANNU
     5AL COSTS',/11X,'MAINTENANCE  $',F10.0,'  $',F10.0,'  $',F10.0,'  $
     6',F10.0,'  $',F10.0,'  $',F10.0,/11X,'FUEL OIL',6X,F10.0,3X,F10.0,
     73X,F10.0,3X,F10.0,3X,F10.0,3X,F10.0,/11X,'LUBE OIL',6X,F10.0,3X,F1
     80.0,3X,F10.0,3X,F10.0,3X,F10.0,3X,F10.0,/11X,'MANNING',7X,F10.0,3X
     9,F10.0,3X,F10.0,3X,F10.0,3X,F10.0,3X,F10.0,/,9X,'TOTAL ANNUAL',/16
     AX,'COSTS   $',F10.0,'  $',F10.0,'  $',F10.0,'  $',F10.0,'  $',F1.
     B0,'  $',F10.0,/,9X,'PRESENT VALUE',/10X,'ANNUAL COSTS  $',F10.0,'
     C $',F10.0,'  $',F10.0,'  $',F10.0,'  $',F10.0,'  $',F10.0,/,9X,'PR
     DESENT VALUE',/11X,'TOTAL COSTS  $',F10.0,'  $',F10.0,'  $',F10.0,'
     E  $',F10.0,'  $',F10.0,'  $',F10.0,//,9X,'WEIGHT(TONS)',4X,F10.0,3
     FX,F10.0,3X,F10.0,3X,F10.0,3X,F10.0,3X,F10.0,/,9X,'AVAILABILITY',4X
     G,F10.3,3X,F10.3,3X,F10.3,3X,F10.3,3X,F10.3,3X,F10.3)
  998 IF(KSTOP.EQ.1)GO TO 999
      GO TO 200
  999 STOP
      END
```


OREGON
RULE
CO.
U.S.A.